US009109511B2

(12) **United States Patent**
Ingersoll et al.

(10) **Patent No.: US 9,109,511 B2**
(45) **Date of Patent: Aug. 18, 2015**

(54) **SYSTEM AND METHODS FOR OPTIMIZING EFFICIENCY OF A HYDRAULICALLY ACTUATED SYSTEM**

(75) Inventors: **Eric D. Ingersoll**, Cambridge, MA (US); **Justin A. Aborn**, Hingham, MA (US); **Matthew Blieske**, Francestown, NH (US)

(73) Assignee: **General Compression, Inc.**, Newton, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 280 days.

(21) Appl. No.: **13/294,660**

(22) Filed: **Nov. 11, 2011**

(65) **Prior Publication Data**

US 2012/0057998 A1 Mar. 8, 2012

Related U.S. Application Data

(63) Continuation of application No. 12/977,724, filed on Dec. 23, 2010.

(60) Provisional application No. 61/290,107, filed on Dec. 24, 2009.

(51) **Int. Cl.**
F04B 9/10 (2006.01)
F02C 6/16 (2006.01)

(52) **U.S. Cl.**
CPC . ***F02C 6/16*** (2013.01); *Y02E 60/15* (2013.01); *Y02T 50/671* (2013.01)

(58) **Field of Classification Search**
CPC Y02E 60/15; F04B 9/10
USPC 60/425; 91/519; 417/396, 399, 401, 403
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

114,297 A 5/1871 Ivens et al.
224,081 A 2/1880 Eckart

(Continued)

FOREIGN PATENT DOCUMENTS

GB 2013318 8/1979
WO WO 90/03516 4/1990

(Continued)

OTHER PUBLICATIONS

Ahrens, F. W., "Preliminary Evaluation of the Use of Hydraulic Air Compressors in Water-Compensated Reservoir Compressed Air Storage Power Plants," NTIS, Prepared for CAES Technology Symposium 1978, May 15-17, 1978, Pacific Grove, CA, Argonne National Laboratory, Argonne, Illinois, 24 pages.

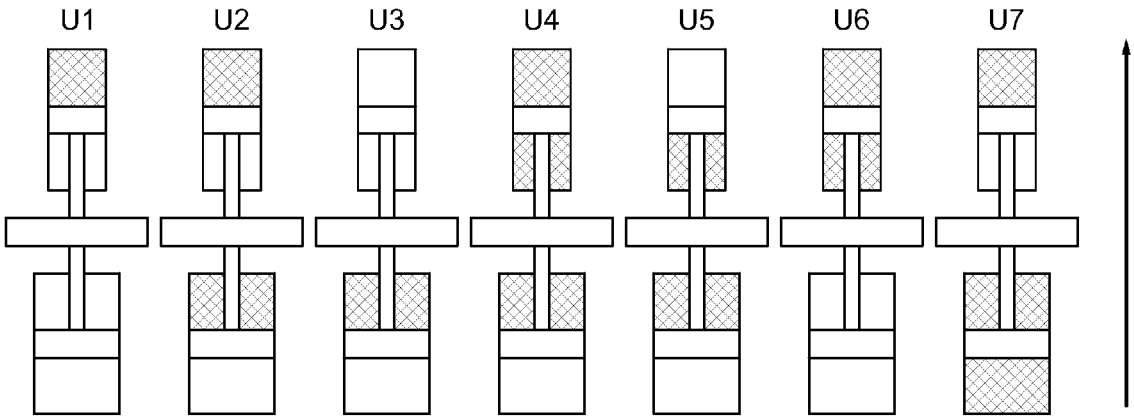
(Continued)

Primary Examiner — F. Daniel Lopez
(74) *Attorney, Agent, or Firm* — Goodwin Procter LLP

(57) **ABSTRACT**

Systems and methods for efficiently operating a hydraulically actuated device/system are described herein. For example, systems and methods for efficiently operating a gas compression and expansion energy storage system are disclosed herein. Systems and methods are provided for controlling and operating the hydraulic actuators used within a hydraulically actuated device/system, such as, for example, a gas compression and/or expansion energy system, within a desired efficiency range of the hydraulic pump(s)/motor(s) used to supply or receive pressurized hydraulic fluid to or from the hydraulic actuators. In such a system, a variety of different operating regimes can be used depending on the desired output gas pressure and the desired stored pressure of the compressed gas. Hydraulic cylinders used to drive working pistons within the system can be selectively actuated to achieve varying force outputs to incrementally increase the gas pressure within the system for a given cycle.

18 Claims, 60 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

233,432	A	10/1880	Pitchford
320,482	A	6/1885	Leavitt
874,140	A	12/1907	Valiquet
943,000	A	12/1909	Busby
1,045,961	A	12/1912	Ferranti
1,147,204	A	7/1915	Anheuser
1,230,028	A	6/1917	Rardon
1,353,216	A	9/1920	Carlson
1,369,596	A	2/1921	Yanacopoulos
1,635,524	A	7/1927	Aikman
1,681,280	A	8/1928	Bruckner
1,918,789	A	7/1933	Ttisworth
1,947,304	A	2/1934	Morro
2,025,142	A	12/1935	Zahm et al.
2,042,991	A	6/1936	Harris, Jr.
2,141,703	A	12/1938	Bays
2,150,122	A	3/1939	Kollberg et al.
2,280,100	A	4/1942	Singleton
2,280,845	A	4/1942	Parker
2,339,086	A	8/1944	Makaroff
2,404,660	A	7/1946	Rouleau
2,420,098	A	5/1947	Rouleau
2,454,058	A	11/1948	Hays
2,479,856	A	8/1949	Mitton
2,539,862	A	1/1951	Rushing
2,628,564	A	2/1953	Jacobs
2,683,964	A	7/1954	Anxionnaz et al.
2,706,077	A	4/1955	Searcy
2,712,728	A	7/1955	Lewis et al.
2,813,398	A	11/1957	Wilcox
2,824,687	A	2/1958	Osterkamp
2,829,501	A	4/1958	Walls
2,880,759	A	4/1959	Wisman
2,898,183	A	8/1959	Fauser
3,014,639	A	12/1961	Boli
3,041,842	A	7/1962	Heinecke
3,232,524	A	2/1966	Rice at al.
3,236,512	A	2/1966	Caslav et al.
3,269,121	A	8/1966	Ludwig
3,355,096	A	11/1967	Hornschuch
3,523,192	A	8/1970	Lang
3,530,681	A	9/1970	Dehne
3,538,340	A	11/1970	Lang
3,608,311	A	9/1971	Roesel, Jr.
3,618,470	A	11/1971	Mueller et al.
3,648,458	A	3/1972	McAlister
3,650,636	A	3/1972	Eskeli
3,672,160	A	6/1972	Kim
3,677,008	A	7/1972	Koutz
3,704,079	A	11/1972	Berlyn
3,757,517	A	9/1973	Rigollot
3,792,643	A	2/1974	Scheafer
3,793,848	A	2/1974	Eskeli
3,796,044	A	3/1974	Schwarz
3,801,793	A	4/1974	Goebel
3,802,795	A	4/1974	Nyeste
3,803,847	A	4/1974	McAlister
3,806,733	A	4/1974	Haanen
3,818,801	A	6/1974	Kime
3,832,851	A	9/1974	Kiernan
3,835,918	A	9/1974	Pilarczyk
3,839,863	A	10/1974	Frazier
3,847,182	A	11/1974	Greer
3,854,301	A	12/1974	Cytryn
3,895,493	A	7/1975	Rigollot
3,903,696	A	9/1975	Carman
3,935,469	A	1/1976	Haydock
3,939,356	A	2/1976	Loane
3,942,323	A	3/1976	Maillet
3,945,207	A	3/1976	Hyatt
3,948,049	A	4/1976	Ohms et al.
3,952,516	A	4/1976	Lapp
3,952,723	A	4/1976	Browning
3,958,899	A	5/1976	Coleman, Jr. et al.
3,968,732	A	7/1976	Fitzgerald
3,986,354	A	10/1976	Erb
3,988,592	A	10/1976	Porter
3,988,897	A	11/1976	Strub
3,990,246	A	11/1976	Wilmers
3,991,574	A	11/1976	Frazier
3,996,741	A	12/1976	Herberg
3,998,049	A	12/1976	McKinley et al.
4,008,006	A	2/1977	Bea
4,009,587	A	3/1977	Robinson, Jr. et al.
4,027,993	A	6/1977	Wolff
4,030,303	A	6/1977	Kraus et al.
4,031,702	A	6/1977	Burnett et al.
4,031,704	A	6/1977	Moore et al.
4,041,708	A	8/1977	Wolff
4,050,246	A	9/1977	Bourquardez
4,053,395	A	10/1977	Switzgable
4,055,950	A	11/1977	Grossman
4,058,979	A	11/1977	Germain
4,079,586	A	3/1978	Kincaid, Jr.
4,079,591	A	3/1978	Derby
4,089,744	A	5/1978	Cahn
4,090,940	A	5/1978	Switzgable
4,095,118	A	6/1978	Rathbun
4,100,745	A	7/1978	Gyarmathy et al.
4,104,955	A	8/1978	Murphy
4,108,077	A	8/1978	Laing
4,109,465	A	8/1978	Plen
4,110,987	A	9/1978	Cahn et al.
4,112,311	A	9/1978	Theyse
4,117,342	A	9/1978	Melley, Jr.
4,117,343	A	9/1978	Hoffelns
4,117,696	A	10/1978	Fawcett et al.
4,118,637	A	10/1978	Tackett
4,124,182	A	11/1978	Loeb
4,124,805	A	11/1978	Jacoby
4,126,000	A	11/1978	Funk
4,136,432	A	1/1979	Melley, Jr.
4,137,015	A	1/1979	Grossman
4,142,368	A	3/1979	Mantegani
4,143,522	A	3/1979	Hamrick
4,147,204	A	4/1979	Pfenninger
4,149,092	A	4/1979	Cros
4,150,547	A	4/1979	Hobson
4,154,292	A	5/1979	Herrick
4,167,372	A	9/1979	Tackett
4,170,878	A	10/1979	Jahnig
4,173,431	A	11/1979	Smith
4,189,925	A	2/1980	Long
4,197,700	A	4/1980	Jahnig
4,197,715	A	4/1980	Fawcett et al.
4,201,514	A	5/1980	Huetter
4,204,126	A	5/1980	Diggs
4,206,601	A	6/1980	Eberle
4,206,608	A	6/1980	Bell
4,209,982	A	7/1980	Pitts
4,215,548	A	8/1980	Beremand
4,220,006	A	9/1980	Kindt
4,229,143	A	10/1980	Pucher
4,229,661	A	10/1980	Mead et al.
4,232,253	A	11/1980	Mortelmans
4,236,083	A	11/1980	Kenney
4,237,692	A	12/1980	Ahrens et al.
4,242,878	A	1/1981	Brinkerhoff
4,246,978	A	1/1981	Schulz et al.
4,262,735	A	4/1981	Courrege
4,265,599	A	5/1981	Morton
4,273,514	A	6/1981	Shore et al.
4,274,010	A	6/1981	Lawson-Tancred
4,275,310	A	6/1981	Summers et al.
4,281,256	A	7/1981	Ahrens
4,293,323	A	10/1981	Cohen
4,299,198	A	11/1981	Woodhull
4,302,684	A	11/1981	Gogins
4,304,103	A	12/1981	Hamrick
4,311,011	A	1/1982	Lewis
4,316,096	A	2/1982	Syverson
4,317,439	A	3/1982	Emmerling
4,329,842	A	5/1982	Hoskinson
4,335,093	A	6/1982	Salomon

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,335,867 A 6/1982 Bihlmaier
4,340,822 A 7/1982 Gregg
4,341,072 A 7/1982 Clyne
4,348,863 A 9/1982 Taylor et al.
4,353,214 A 10/1982 Gardner
4,354,420 A 10/1982 Bianchetta
4,355,956 A 10/1982 Ringrose et al.
4,358,250 A 11/1982 Payne
4,362,462 A 12/1982 Blotenberg
4,363,703 A 12/1982 ElDifrawi
4,367,786 A 1/1983 Hafner et al.
4,368,692 A 1/1983 Kita
4,368,775 A 1/1983 Ward
4,370,559 A 1/1983 Langley, Jr.
4,372,114 A 2/1983 Burnham
4,372,332 A 2/1983 Mast
4,375,387 A 3/1983 deFilippi et al.
4,380,419 A 4/1983 Morton
4,393,752 A 7/1983 Meier
4,411,136 A 10/1983 Funk
4,421,661 A 12/1983 Claar et al.
4,426,846 A 1/1984 Bailey
4,428,711 A 1/1984 Archer
4,435,131 A 3/1984 Ruben
4,466,244 A 8/1984 Wu
4,478,556 A 10/1984 Gozzi
4,537,558 A 8/1985 Tsunoda et al.
4,585,039 A 4/1986 Hamilton
4,593,202 A 6/1986 Dickinson
4,603,551 A 8/1986 Wood
4,610,369 A 9/1986 Mercier
4,706,685 A 11/1987 Jones, Jr. et al.
4,714,411 A 12/1987 Searle
4,761,118 A 8/1988 Zanarini et al.
4,765,225 A 8/1988 Birchard
4,784,579 A 11/1988 Gazzera
4,849,648 A 7/1989 Longardner
4,959,958 A 10/1990 Nishikawa et al.
5,099,648 A 3/1992 Angle
5,138,936 A 8/1992 Kent
5,142,870 A 9/1992 Angle
5,161,865 A 11/1992 Higashimate et al.
5,169,295 A 12/1992 Stogner et al.
5,179,837 A 1/1993 Sieber
5,184,936 A 2/1993 Nojima
5,253,619 A 10/1993 Richeson et al.
5,259,738 A 11/1993 Salter et al.
5,322,418 A 6/1994 Comer
5,387,089 A 2/1995 Stogner et al.
5,394,695 A 3/1995 Sieber
5,537,822 A 7/1996 Shnaid et al.
5,564,912 A 10/1996 Peck et al.
5,584,664 A 12/1996 Elliott et al.
5,622,478 A 4/1997 Elliott et al.
5,634,340 A 6/1997 Grennan
5,674,053 A 10/1997 Paul et al.
5,716,197 A 2/1998 Paul et al.
5,769,610 A 6/1998 Paul et al.
5,771,693 A 6/1998 Coney
5,782,612 A 7/1998 Margardt
5,807,083 A 9/1998 Tomoiu
5,839,270 A 11/1998 Jirnov et al.
5,863,186 A 1/1999 Green et al.
5,993,170 A 11/1999 Stevens et al.
6,026,349 A 2/2000 Heneman
6,052,992 A 4/2000 Eroshenko
6,113,357 A 9/2000 Dobbs
6,145,311 A 11/2000 Cyphelly
6,206,660 B1 3/2001 Coney et al.
RE37,603 E 3/2002 Coney
6,371,145 B1 4/2002 Bardon
6,371,733 B1 4/2002 Renfro
6,397,794 B1 6/2002 Sanderson et al.
6,446,587 B1 9/2002 Sanderson et al.
6,460,450 B1 10/2002 Sanderson et al.
6,499,288 B1 12/2002 Knight
6,558,134 B2 5/2003 Serafin et al.
6,568,169 B2 5/2003 Conde et al.
6,568,911 B1 5/2003 Brightwell et al.
6,638,024 B1 10/2003 Hancock
6,652,241 B1 11/2003 Alder
6,652,243 B2 11/2003 Krasnov
6,655,155 B2 12/2003 Bishop
6,695,591 B2 2/2004 Grimmer et al.
6,711,984 B2 3/2004 Tagge et al.
6,725,671 B2 4/2004 Bishop
6,733,253 B2 5/2004 Vockroth
6,817,185 B2 11/2004 Coney et al.
6,829,978 B2 12/2004 Sanderson et al.
6,854,377 B2 2/2005 Sanderson et al.
6,913,447 B2 7/2005 Fox et al.
6,915,765 B1 7/2005 Sanderson et al.
6,925,973 B1 8/2005 Sanderson et al.
6,957,632 B1 10/2005 Carlson et al.
6,959,546 B2 11/2005 Corcoran
6,994,104 B2 2/2006 Bishop et al.
6,997,685 B2 2/2006 Lemmen
7,001,158 B2 2/2006 Dunn
7,007,589 B1 3/2006 Sanderson
7,011,469 B2 3/2006 Sanderson et al.
7,021,602 B2 4/2006 Davis et al.
RE39,249 E 8/2006 Link, Jr.
7,210,496 B2 5/2007 Suzuki
7,219,682 B2 5/2007 Agnew et al.
7,257,952 B2 8/2007 Bishop et al.
7,308,361 B2 12/2007 Enis et al.
7,377,492 B2 5/2008 Vrana et al.
7,395,748 B2 7/2008 Krimbacher
7,488,159 B2 2/2009 Bhatt et al.
7,527,482 B2 5/2009 Ursan et al.
7,530,300 B2 5/2009 Hornstein
7,543,668 B1 6/2009 Schechter
7,604,064 B2 10/2009 Irwin, Jr.
7,610,955 B2 11/2009 Irwin, Jr.
7,640,736 B2 1/2010 Arbel et al.
7,656,055 B2 2/2010 Torres et al.
7,663,255 B2 2/2010 Kim et al.
7,696,632 B1 4/2010 Fuller
7,802,426 B2 9/2010 Bollinger
7,832,207 B2 11/2010 McBride et al.
7,874,155 B2 1/2011 McBride et al.
7,900,444 B1 3/2011 McBride et al.
8,037,678 B2 * 10/2011 McBride et al. 60/413
8,161,741 B2 * 4/2012 Ingersoll et al. 60/425
2003/0180155 A1 9/2003 Coney et al.
2005/0180864 A1 8/2005 Ursan et al.
2006/0078445 A1 4/2006 Carter, III et al.
2006/0218908 A1 10/2006 Abou-Raphael
2006/0248886 A1 11/2006 Ma
2007/0187918 A1 8/2007 Mizuno
2008/0060862 A1 3/2008 Schlele et al.
2008/0163618 A1 7/2008 Paul
2009/0260361 A1 10/2009 Prueitt
2009/0282822 A1 11/2009 McBride et al.
2009/0301089 A1 12/2009 Bollinger
2010/0018196 A1 1/2010 Li et al.
2010/0089063 A1 4/2010 McBride et al.
2010/0139277 A1 6/2010 McBride et al.
2010/0205960 A1 8/2010 McBride et al.
2010/0229544 A1 9/2010 Bollinger et al.
2010/0307156 A1 12/2010 Bollinger et al.
2010/0326062 A1 12/2010 Fong et al.
2010/0326064 A1 12/2010 Fong et al.
2010/0326066 A1 12/2010 Fong et al.
2010/0326068 A1 12/2010 Fong et al.
2010/0326069 A1 12/2010 Fong et al.
2010/0326075 A1 12/2010 Fong et al.
2010/0329891 A1 12/2010 Fong et al.
2010/0329903 A1 12/2010 Fong et al.
2010/0329909 A1 12/2010 Fong et al.
2011/0023488 A1 2/2011 Fong et al.
2011/0023977 A1 2/2011 Fong et al.
2011/0030359 A1 2/2011 Fong et al.
2011/0030552 A1 2/2011 Fong et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2011/0056193	A1	3/2011	McBride et al.
2011/0056368	A1	3/2011	McBride et al.
2011/0061741	A1	3/2011	Ingersoll et al.
2011/0061836	A1	3/2011	Ingersoll et al.
2011/0062166	A1	3/2011	Ingersoll et al.
2011/0079010	A1	4/2011	McBride et al.
2011/0083438	A1	4/2011	McBride et al.
2011/0131966	A1	6/2011	McBride et al.
2011/0167813	A1	7/2011	McBride et al.
2011/0258999	A1	10/2011	Ingersoll et al.
2011/0259001	A1	10/2011	McBride et al.
2011/0259442	A1	10/2011	McBride et al.

FOREIGN PATENT DOCUMENTS

WO	WO 93/06367	4/1993
WO	WO 98/17492	4/1998
WO	WO 2005/069847	8/2005
WO	WO 2008/139267	11/2008
WO	WO 2009/034548	3/2009
WO	WO 2010/135658	11/2010
WO	WO 2011/079267	6/2011
WO	WO 2011/079271	6/2011

OTHER PUBLICATIONS

Berghmans, J. A. et al., "Performance of a Hydraulic Air Compressor for Use in Compressed Air Energy Storage Power Systems," Smithsonian/NASA ADS Physics Abstract Service, Presented at Symp. on Fluids Eng. in Advanced Energy Conversion Systems, ASME Winter Ann. Meeting, San Francisco, Dec. 10-15.

Carbon Trust, "Hydraulic Transmission System for Large Wind Turbines," Jan. 2007, 1 page.

Erbe, R., "Water Works: Less Expensive Than Oil and Environmentally Friendly, Water-Based Hydraulics Deserve a Closer Look," Machine Design, Sep. 13, 2007, vol. 116, 5 pages.

Hydraulics & Pneumatics, Piston Pumps [online], [retrieved on Oct. 17, 2007]. Retrieved from the Internet: <URL: http://www.hydraulicspneumatics.com/200/FPE/pumps/article/true/6402>, 2007, Penton Media, Inc., 4 pages.

Hydraulics & Pneumatics, Wobble-Plate Piston Pump [online], [retrieved on Oct. 18, 2007]. Retrieved from the Internet: <URL: http://www.hydraulicspneumatics.com/200/issue/article/true/43640>, 2007, Penton Media, Inc., 13 pages.

Moore, J. J. et al., "Conceptual Design Study of Hydraulic Compression for Wind Turbine Driven Air Compression," Final Report, SwRI Project No. 18.18094.01.016, Jun. 6, 2008, Southwest Research institute, 50 pages.

Sanderson, A. E., "Hydraulic System for Control of Power Windmills," undated, 11 pages.

Sanderson Engine Development, "Application of Sanderson Mechanism for Conversion Between Linear and Rotary Motion," [online], [retrieved on May 8, 2008]. Retrieved from the Internet: <URL: http://www.sandersonengine.com/html/projects.html>, 2 pages.

Simetric, "Mass, Weight, Density or Specific Gravity of Liquids," [online], [retrieved on Jan. 2, 2008]. Retrieved from the Internet: <URL: http://www.simetric.co.uk/si_liquids.htm>, 5 pages.

"Swash-plate Type Axial Piston Pumps for Open Circuits in General Industrial Machinery," Kawasaki K3VG, Kawasaki Motor Corp., USA, 2006, 24 pages.

International Search Report and Written Opinion for International Application No. PCT/US2010/062016, mailed Jan. 19, 2012.

Cyphelly et al., "Usage of Compressed Air Storage Systems," Program Elektricity, Final Report May 2004, Ordered by the Swiss Federal Office of Energy.

* cited by examiner

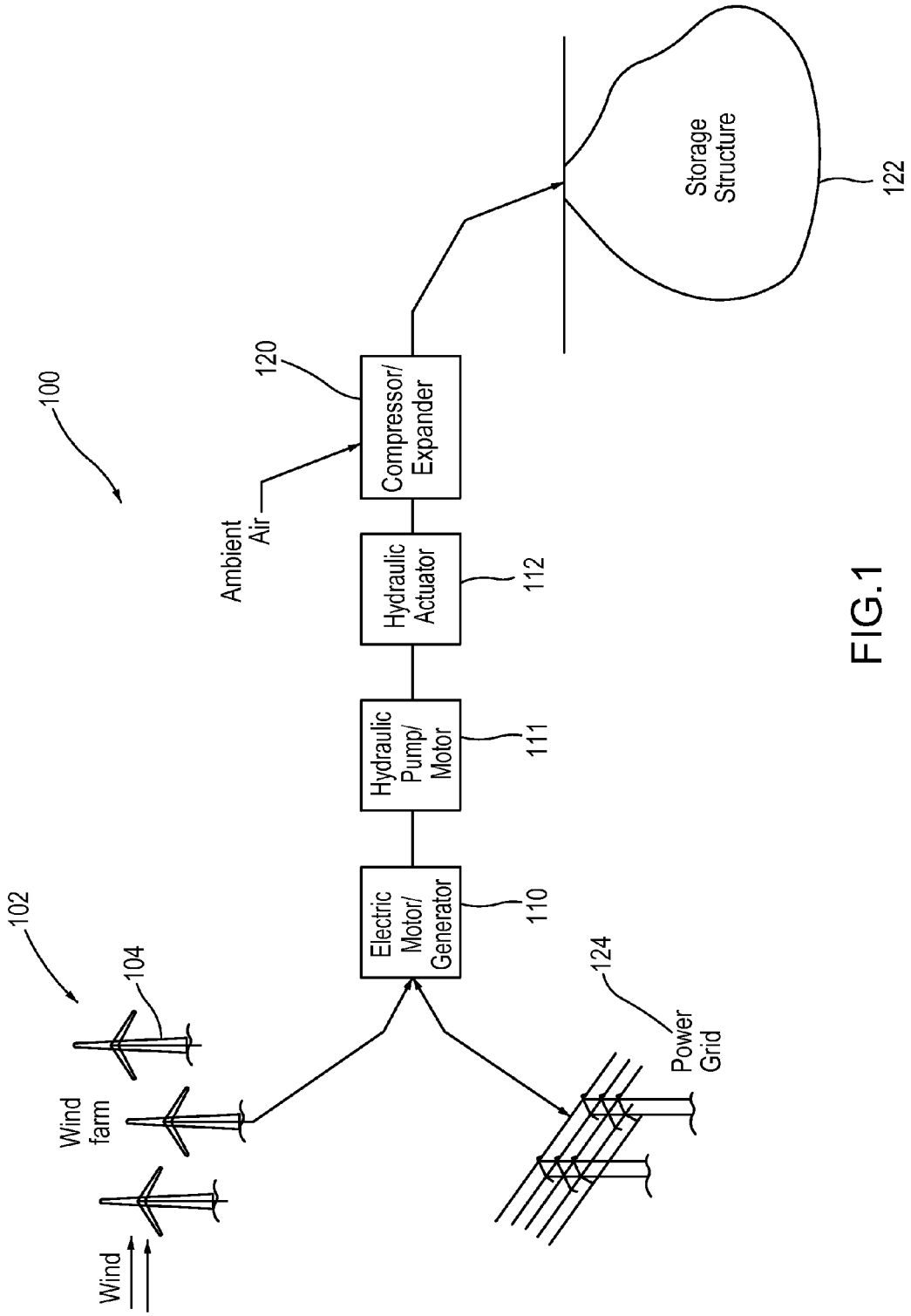

100
102
104
Wind farm
Wind
Electric Motor/ Generator
110
Hydraulic Pump/ Motor
111
Hydraulic Actuator
112
Ambient Air
120
Compressor/ Expander
Storage Structure
122
124
Power Grid

FIG.1

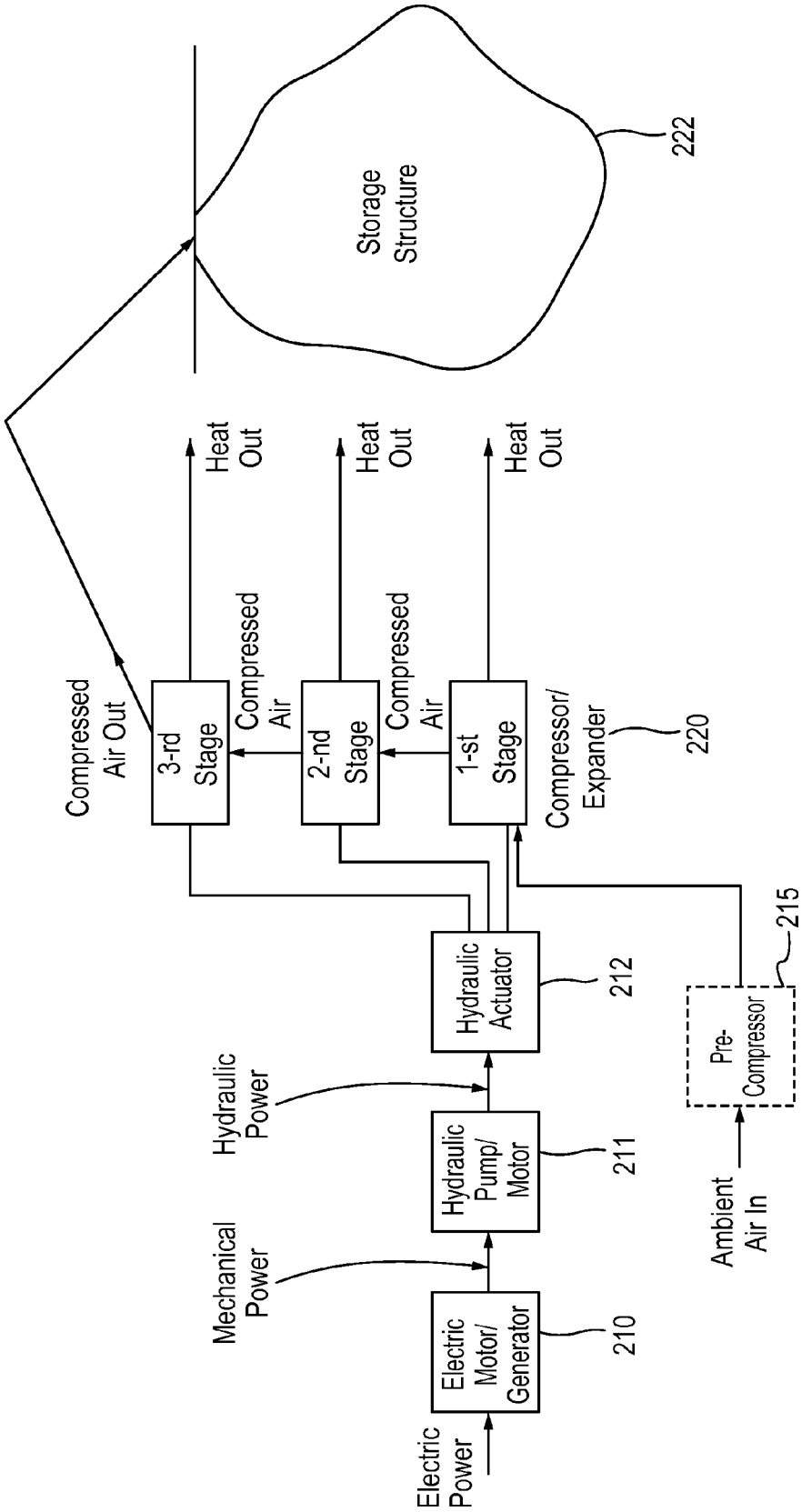

Storage Structure
222
Compressed Air Out
3-rd Stage
Compressed Air
2-nd Stage
Compressed Air
1-st Stage
Compressor/ Expander
220
Heat Out
Heat Out
Heat Out
Hydraulic Actuator
212
Hydraulic Pump/ Motor
211
Electric Motor/ Generator
210
Hydraulic Power
Mechanical Power
Electric Power
Pre-Compressor
215
Ambient Air In

FIG.2A

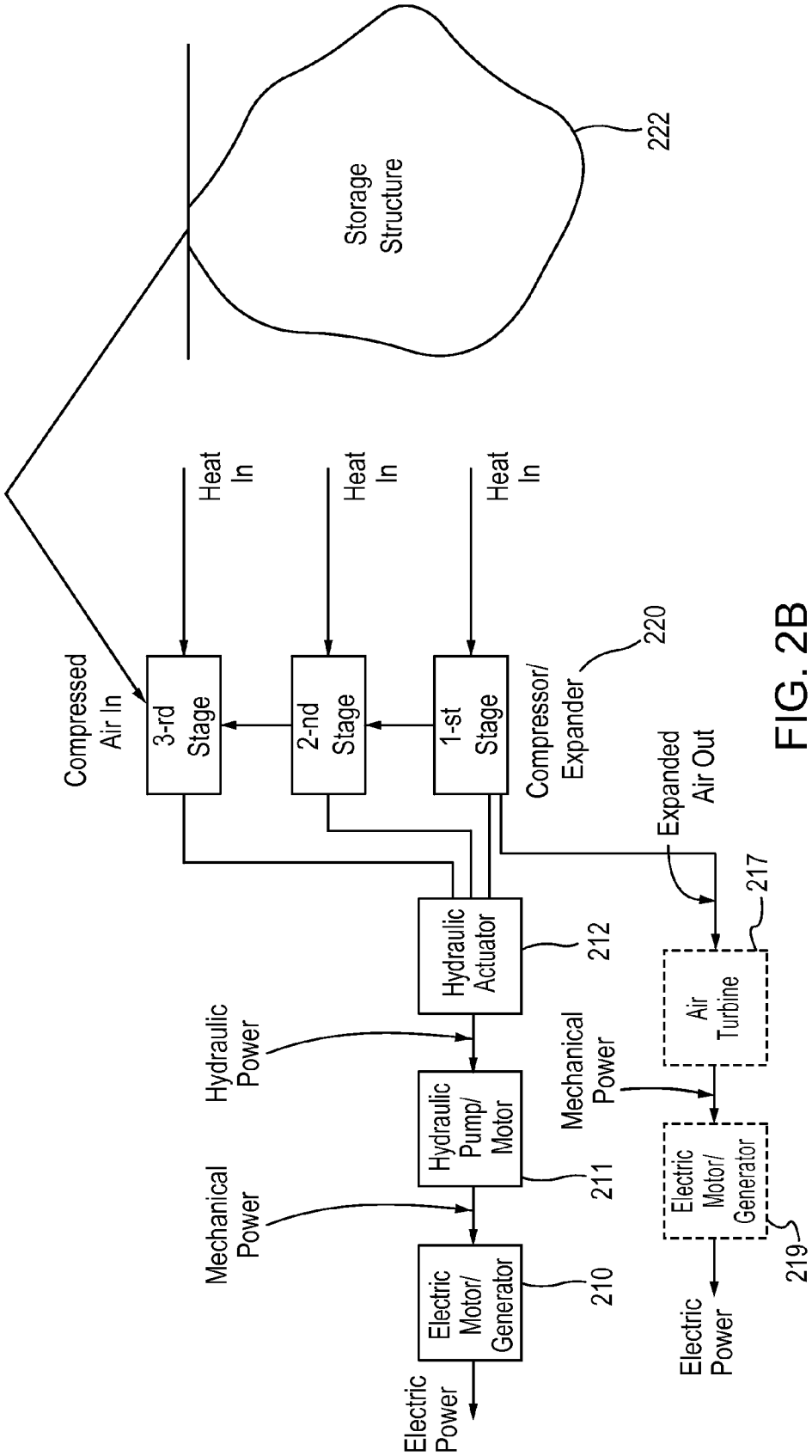

Storage Structure
222
Heat In
Heat In
Heat In
Compressed Air In
3-rd Stage
2-nd Stage
1-st Stage
Compressor/ Expander
220
Expanded Air Out
217
Hydraulic Actuator
212
Hydraulic Power
Hydraulic Pump/ Motor
211
Mechanical Power
Mechanical Power
Electric Motor/ Generator
210
Electric Power
Air Turbine
Electric Motor/ Generator
219
Electric Power

FIG. 2B

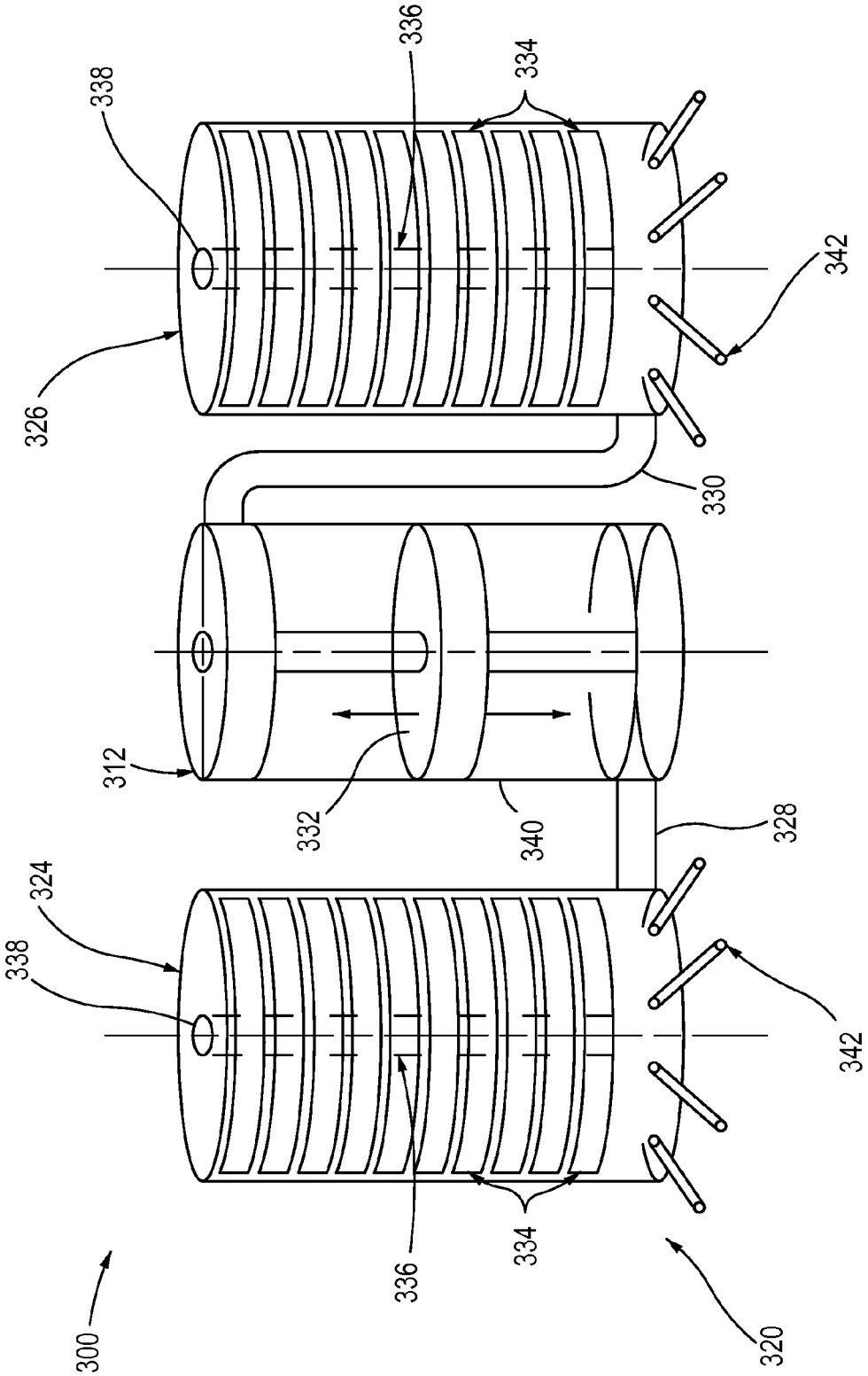


FIG. 3

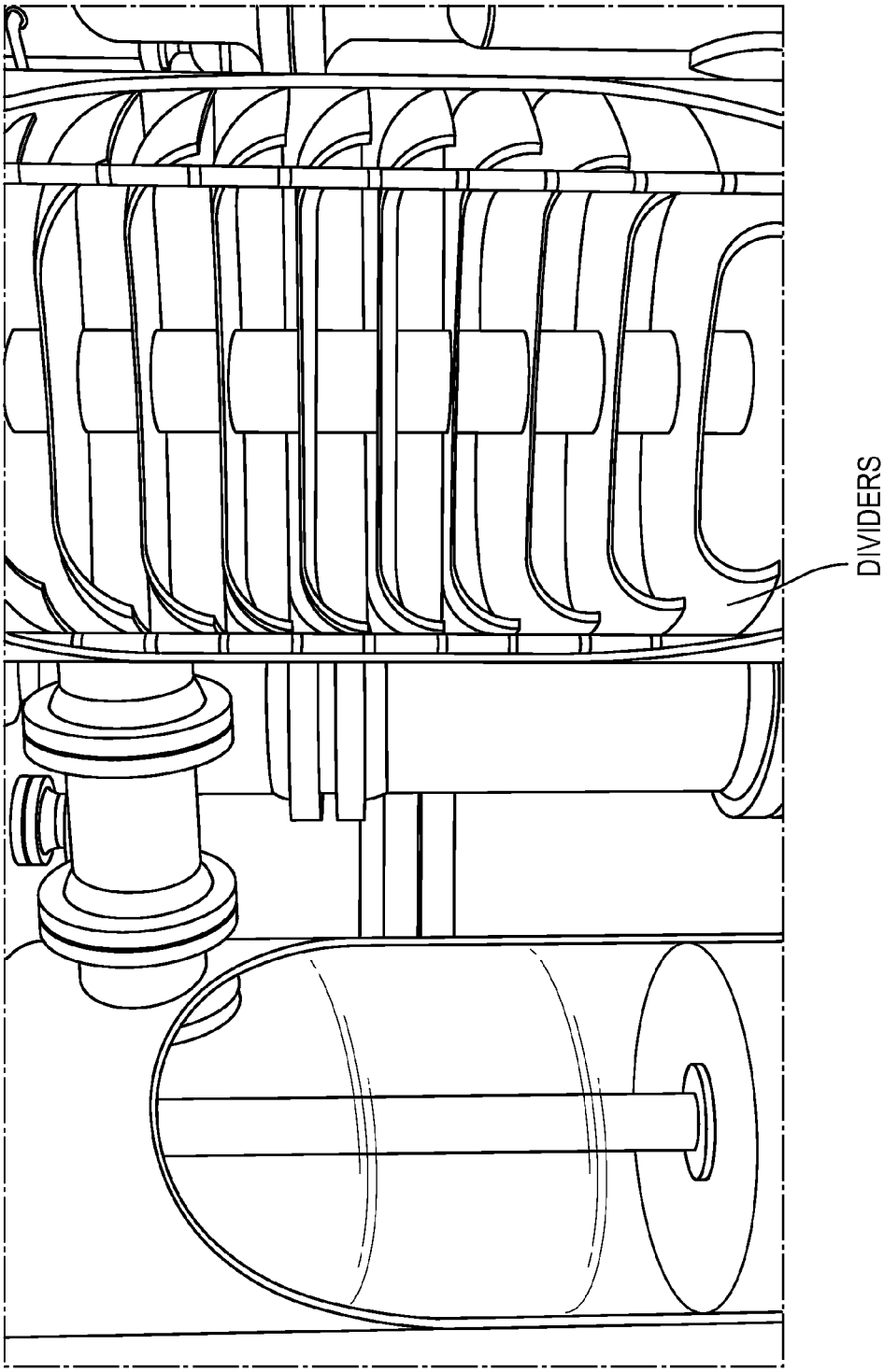


FIG. 4

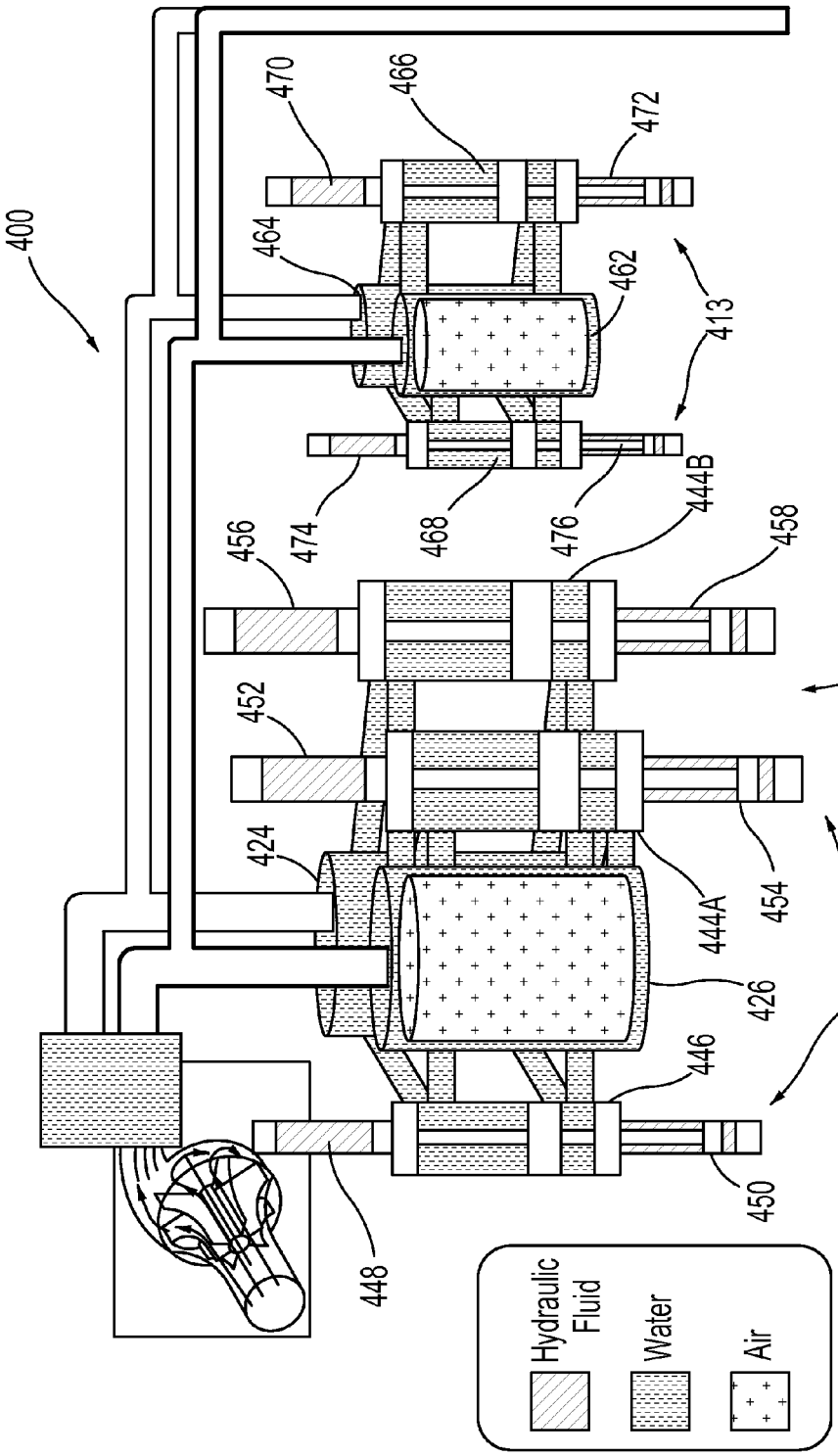

400
470
466
472
464
462
413
474
468
476
444B
456
458
444
452
424
444A
454
426
412
446
448
450
Hydraulic Fluid
Water
Air

FIG. 5A

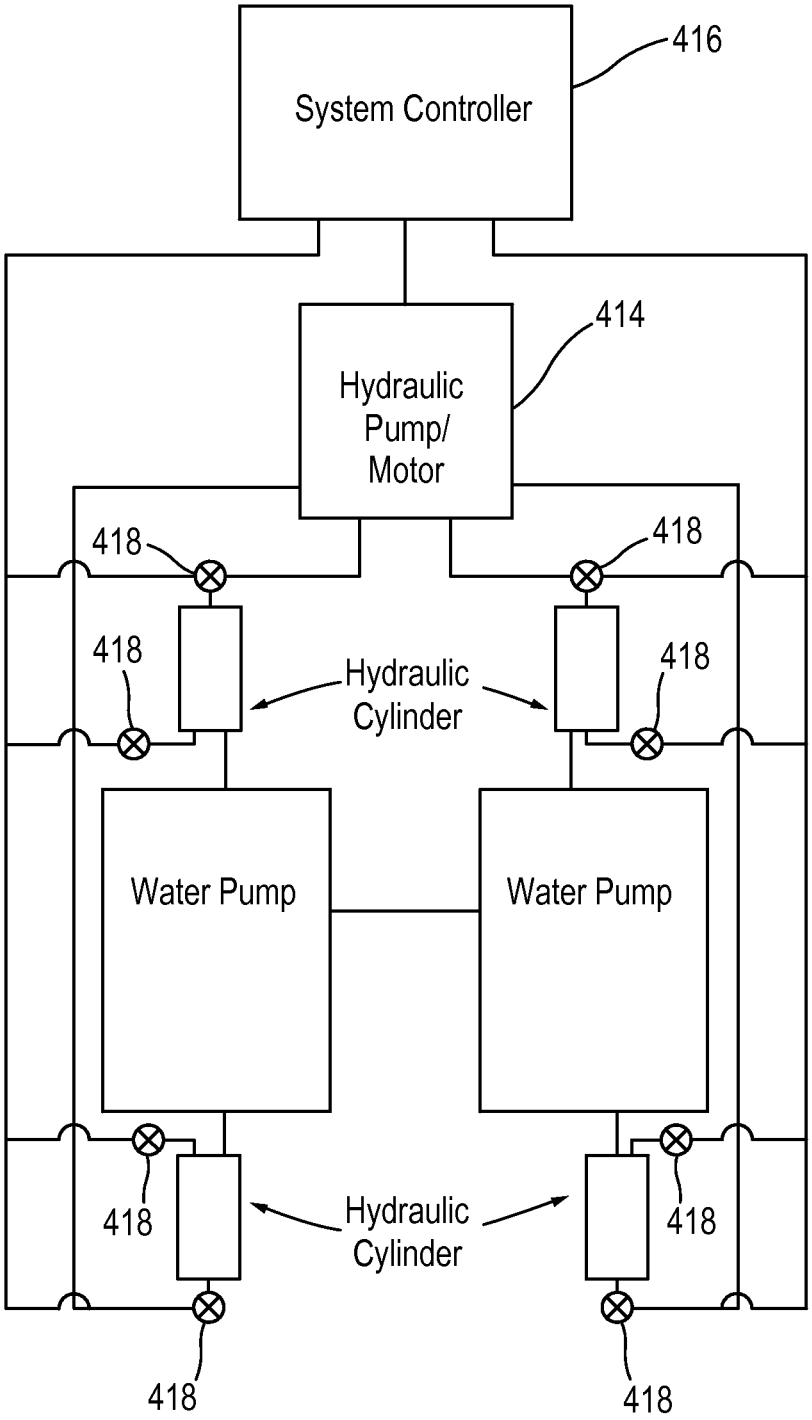

System Controller
416
Hydraulic Pump/ Motor
414
418
418
418
418
Hydraulic Cylinder
Water Pump
Water Pump
418
418
Hydraulic Cylinder
418
418

FIG. 5B

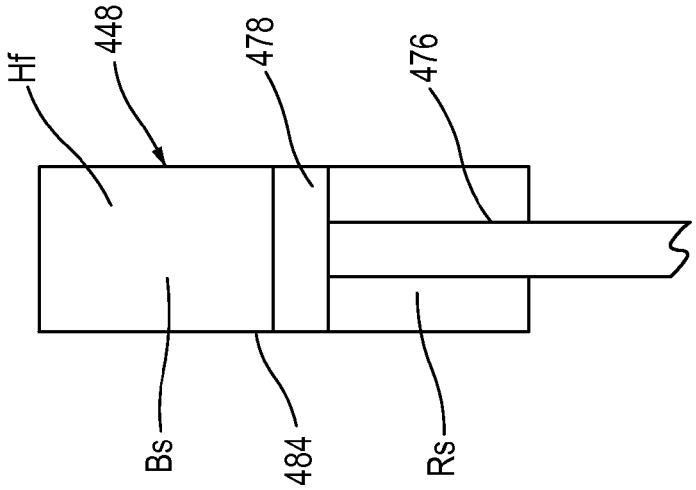


FIG. 6B

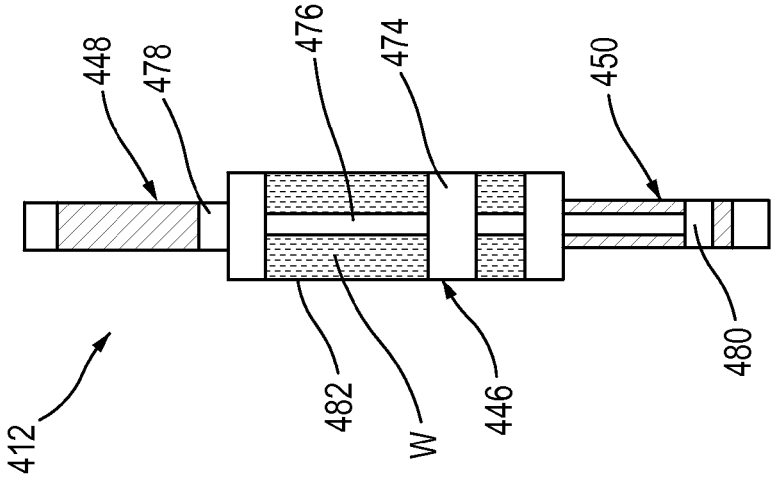


FIG. 6A

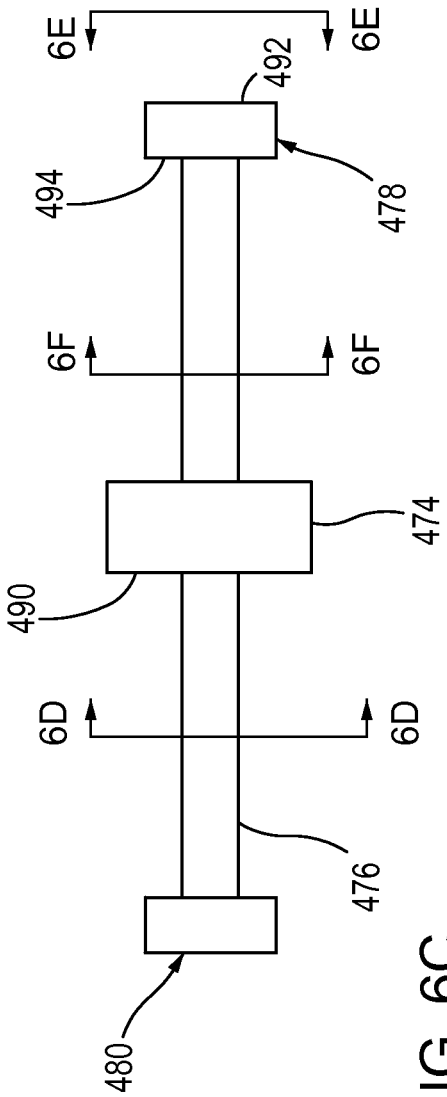


FIG. 6C

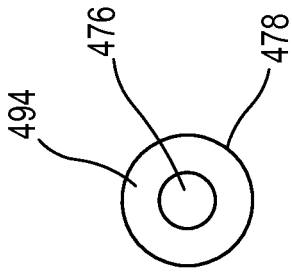


FIG. 6F

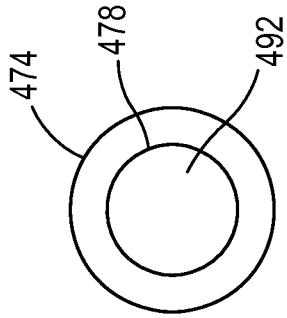


FIG. 6E

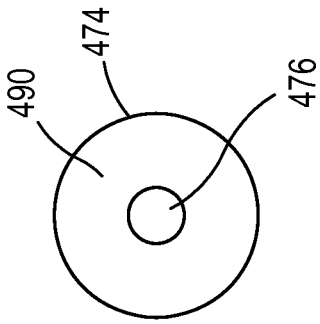


FIG. 6D

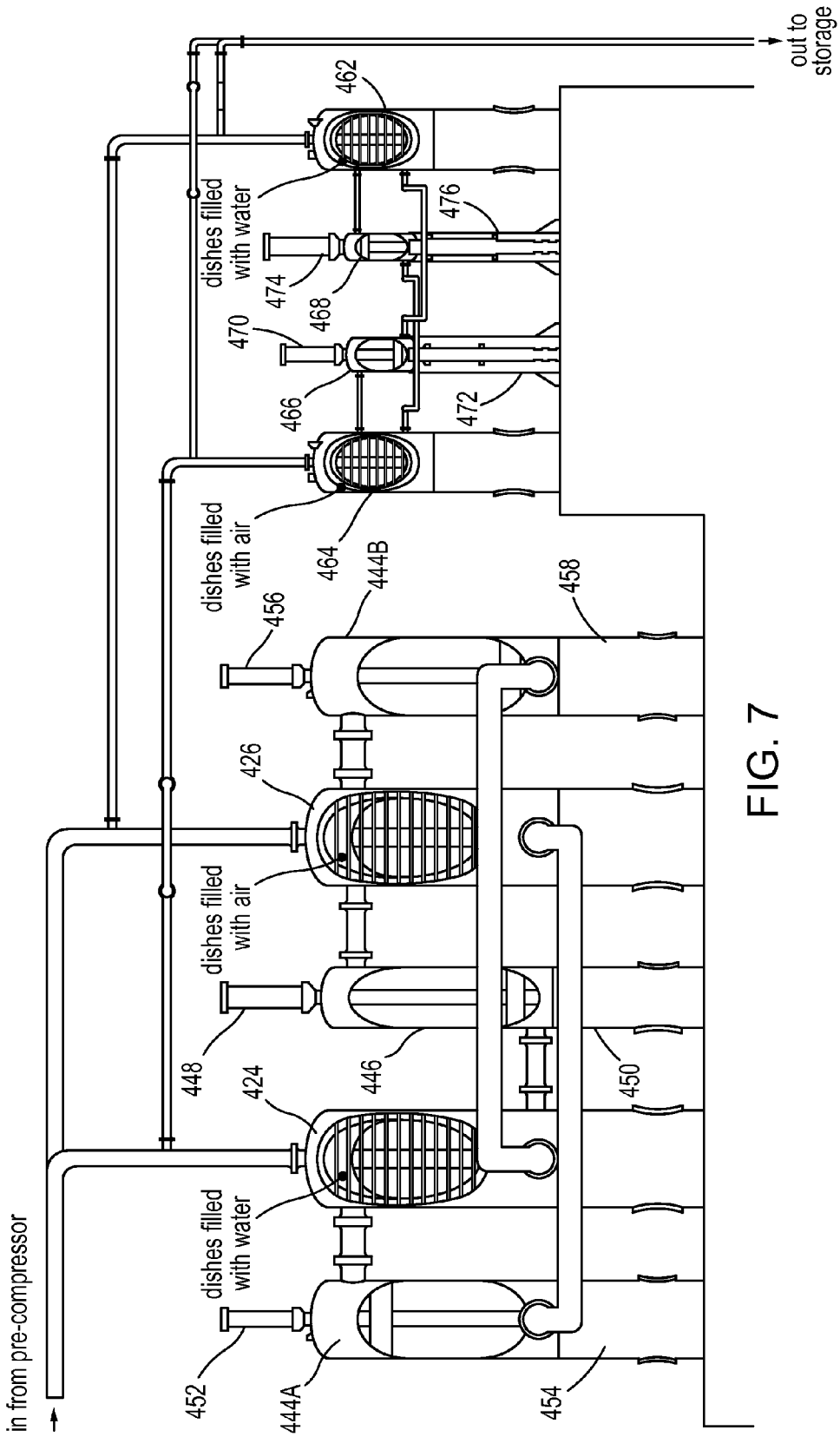

out to storage
462
dishes filled with water
476
474
468
470
466
472
dishes filled with air
464
444B
458
456
426
dishes filled with air
448
446
450
424
dishes filled with water
in from pre-compressor
452
444A
454

FIG. 7

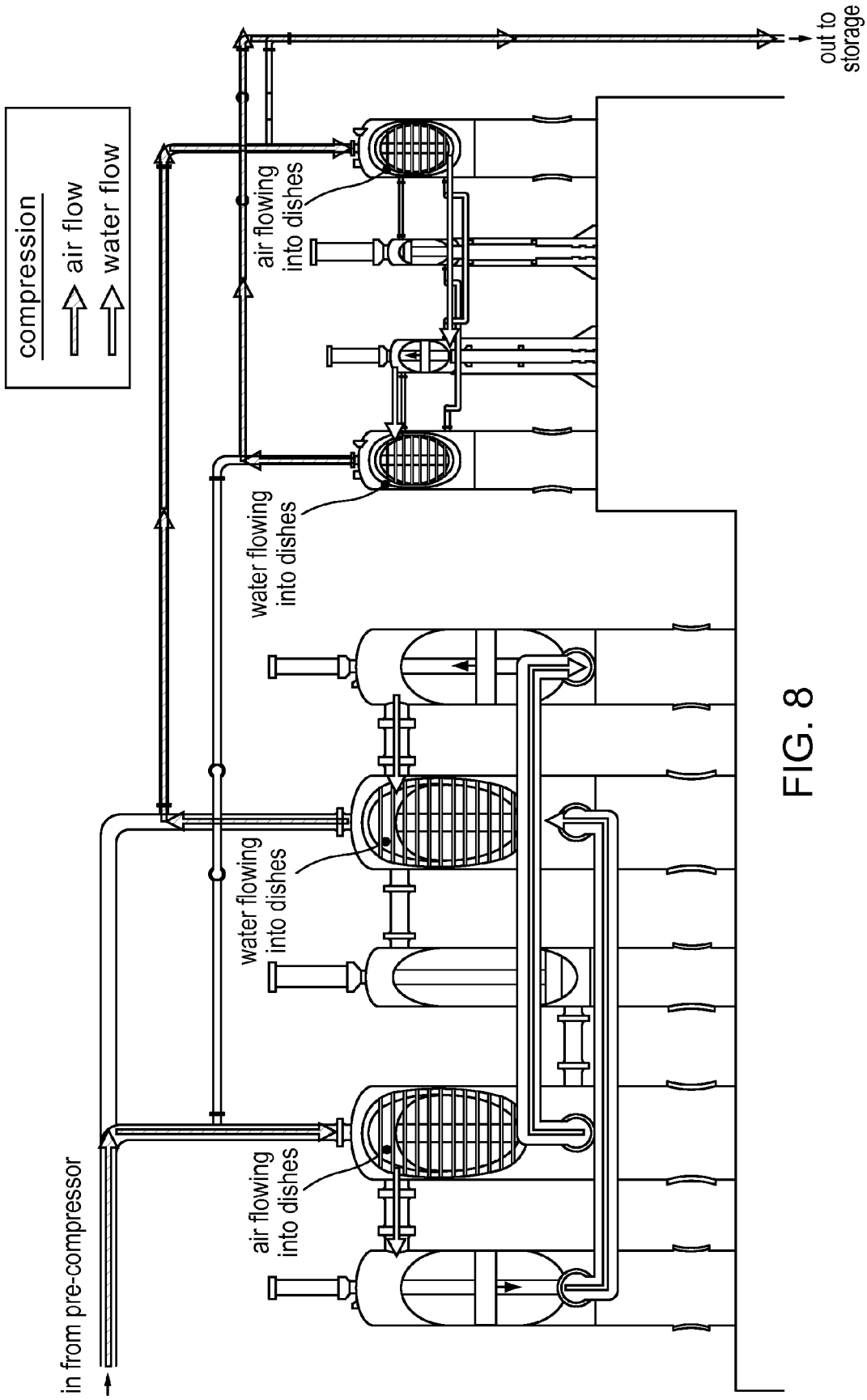

compression
air flow
water flow
in from pre-compressor
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to storage

FIG. 8

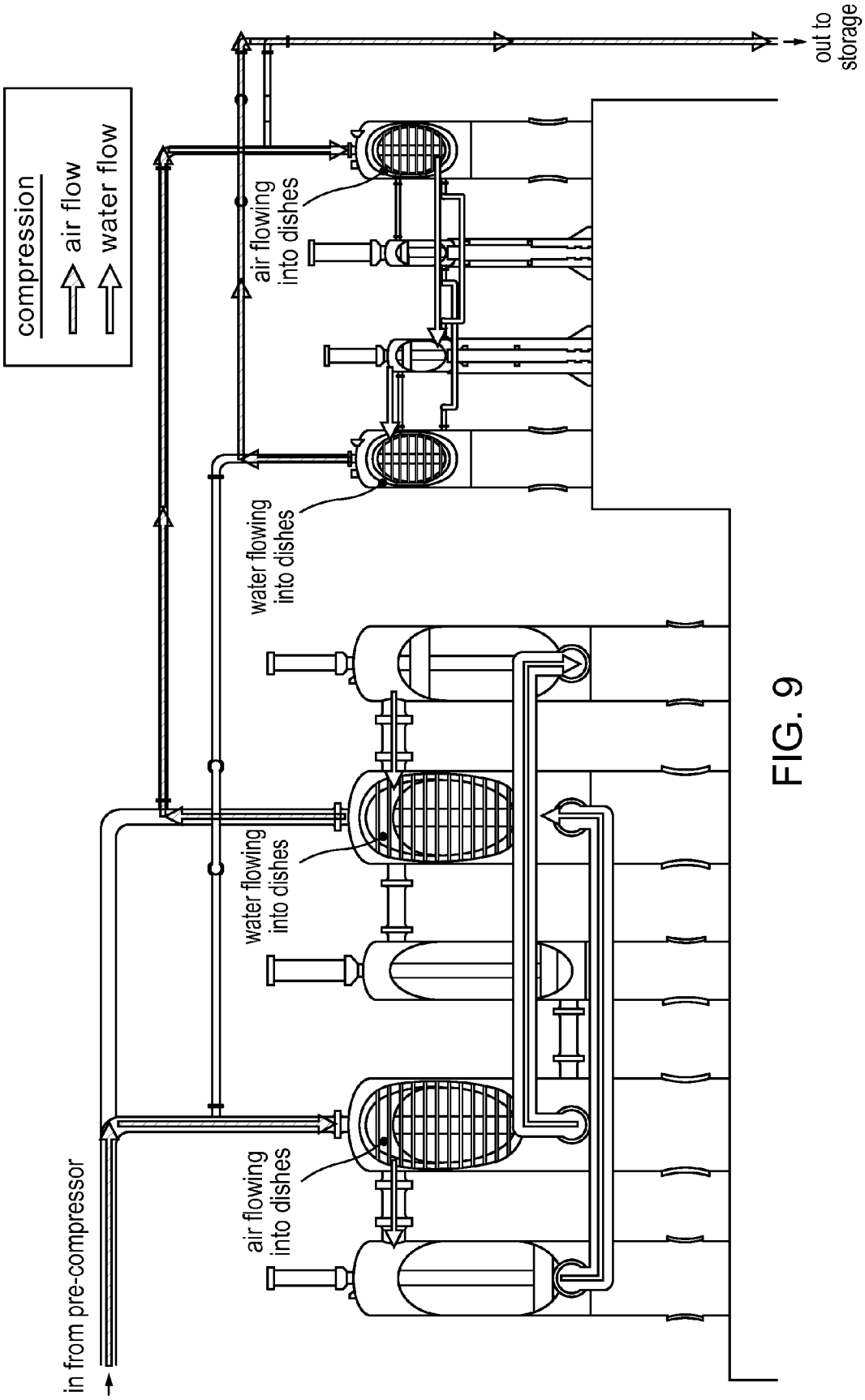

compression
air flow
water flow
in from pre-compressor
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to storage

FIG. 9

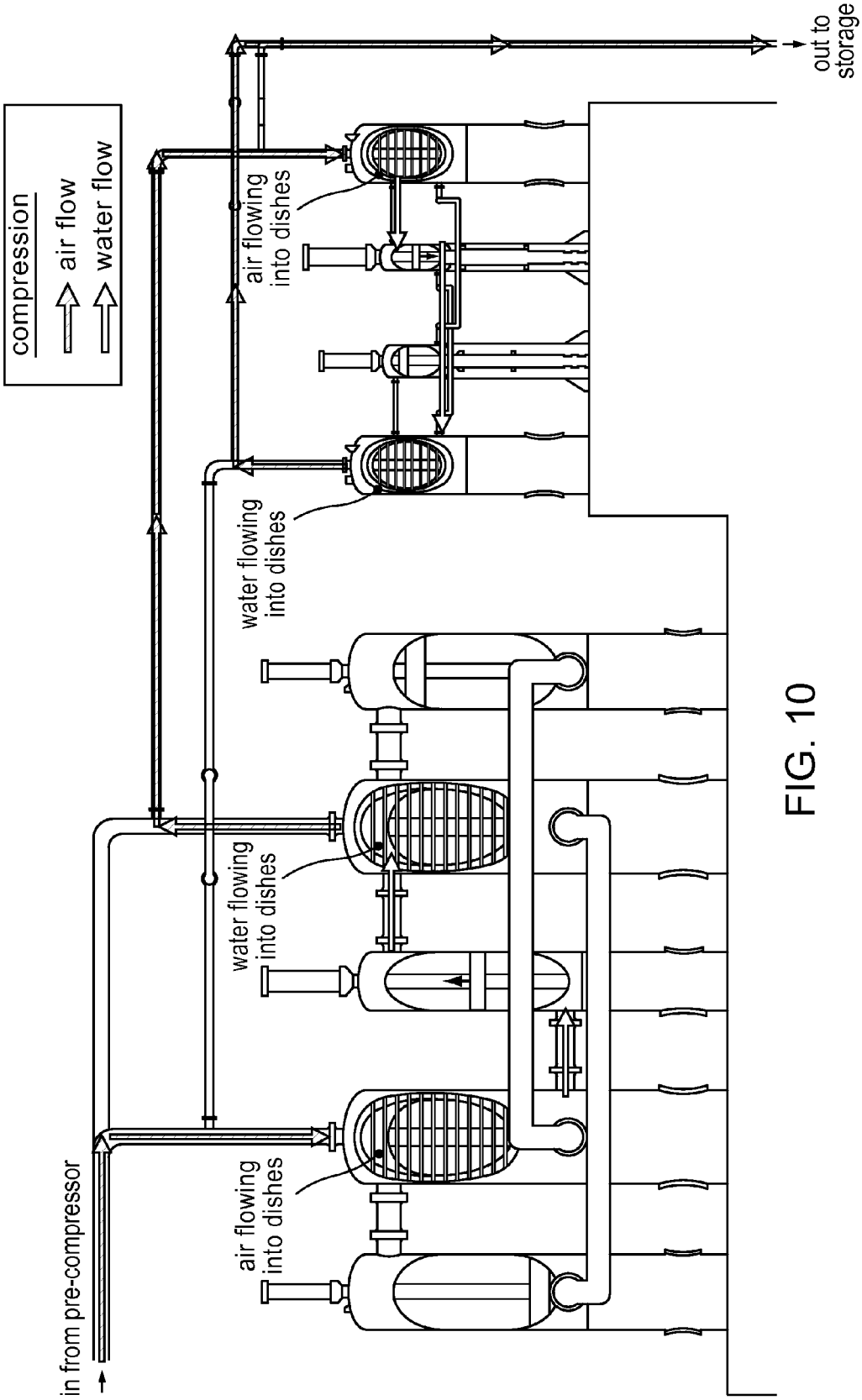

compression
air flow
water flow
in from pre-compressor
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to storage

FIG. 10

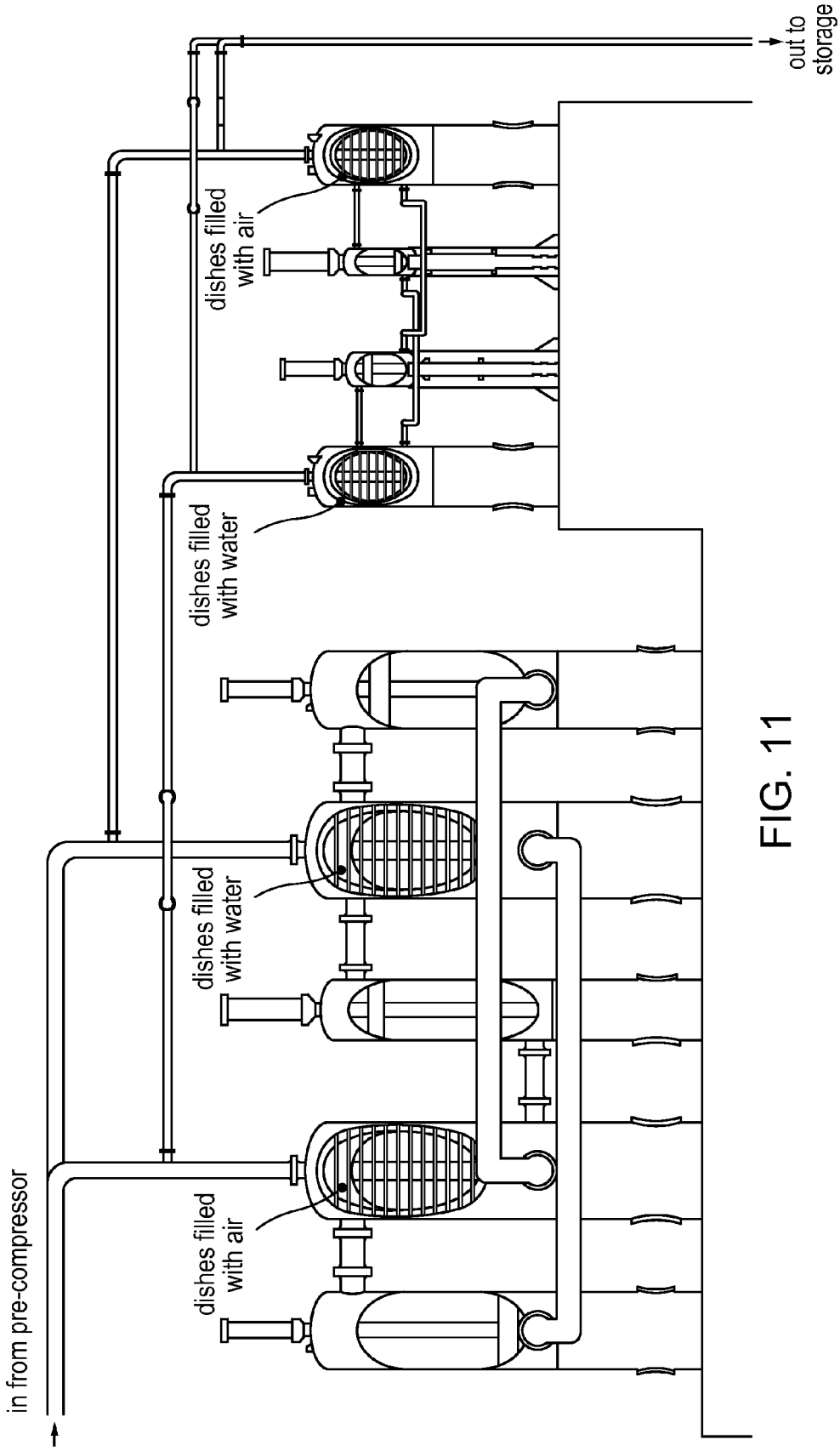

in from pre-compressor
dishes filled with air
dishes filled with water
dishes filled with water
dishes filled with air
out to storage

FIG. 11

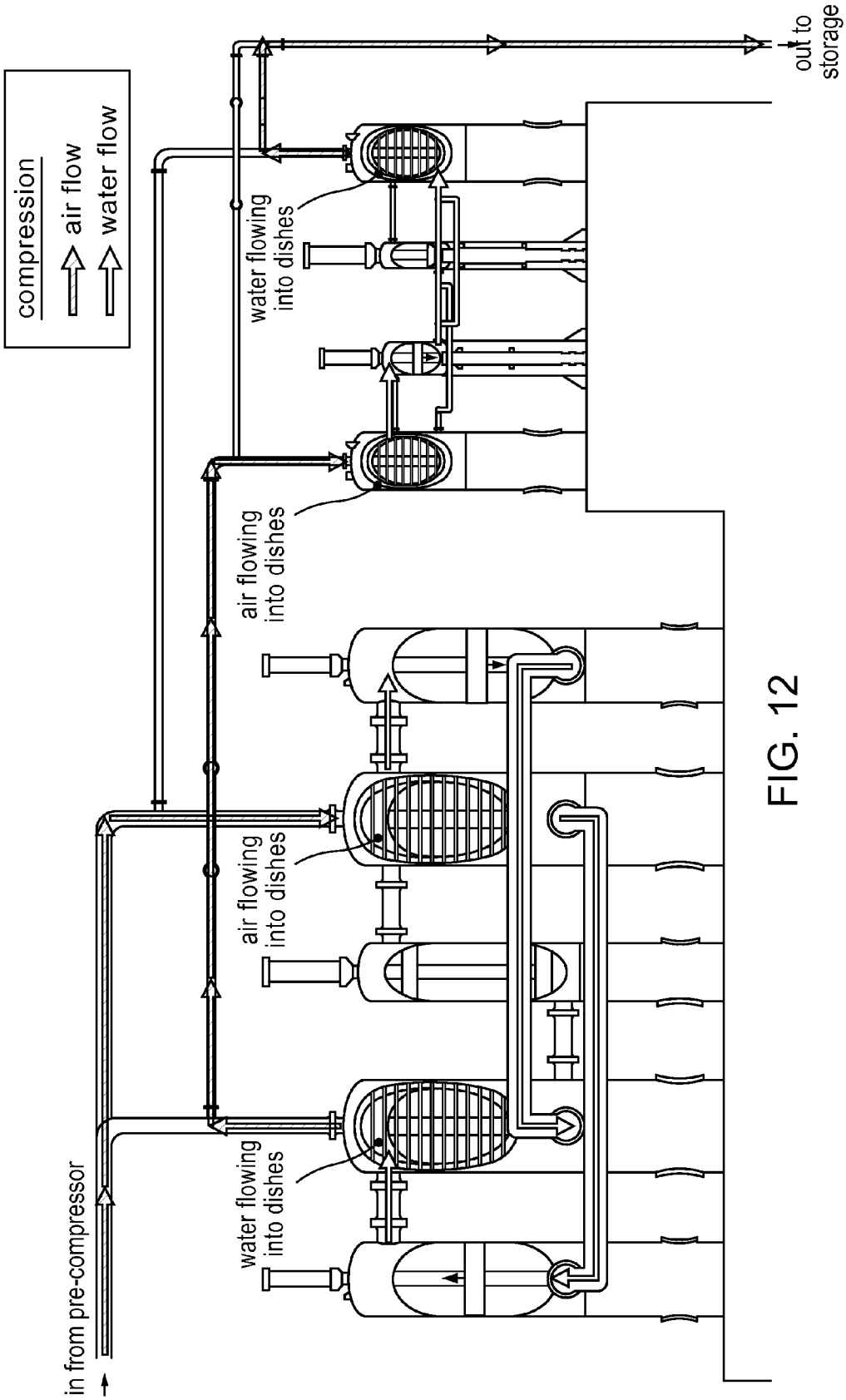

compression
air flow
water flow
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
in from pre-compressor
out to storage

FIG. 12

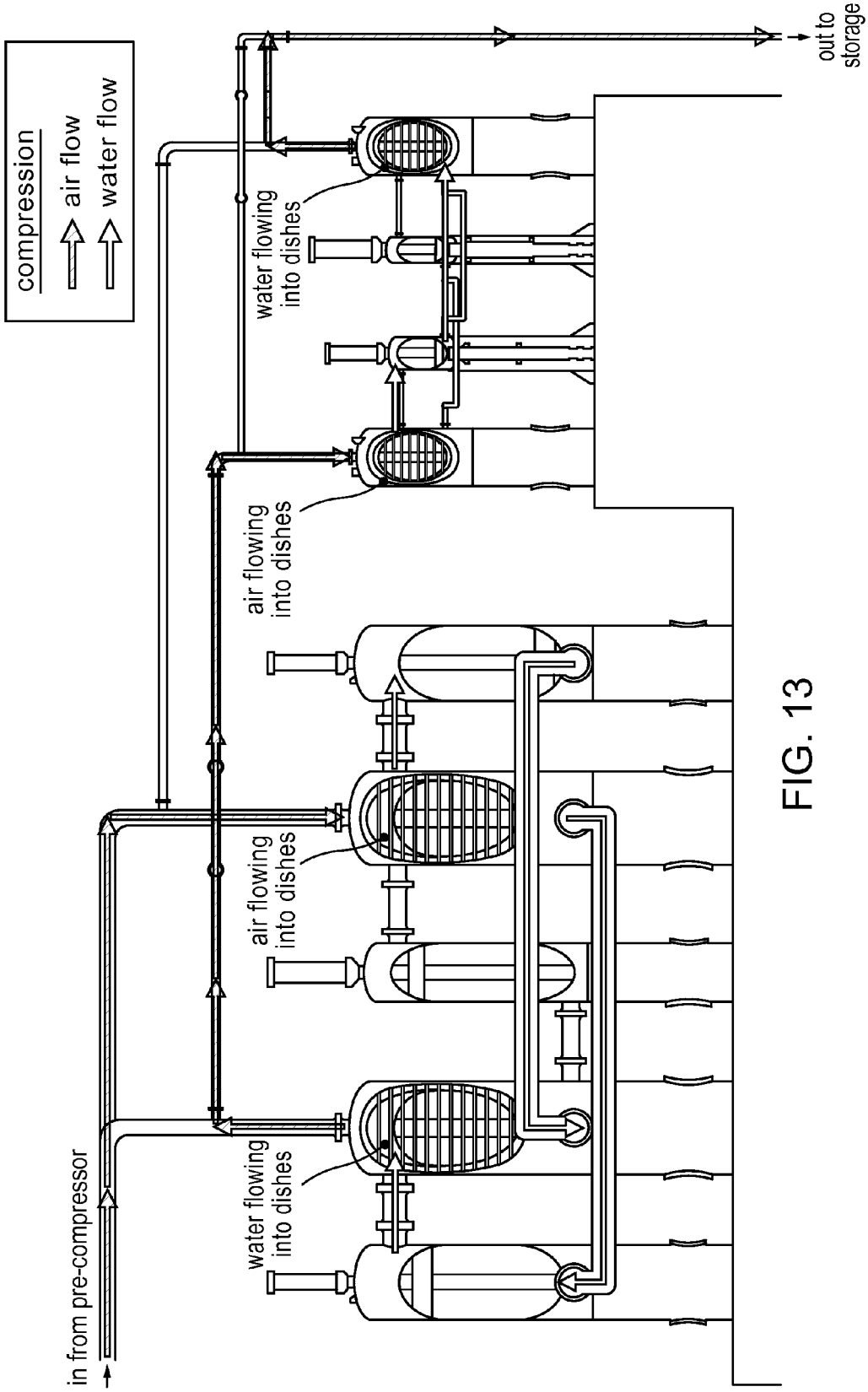

compression
air flow
water flow
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
in from pre-compressor
out to storage

FIG. 13

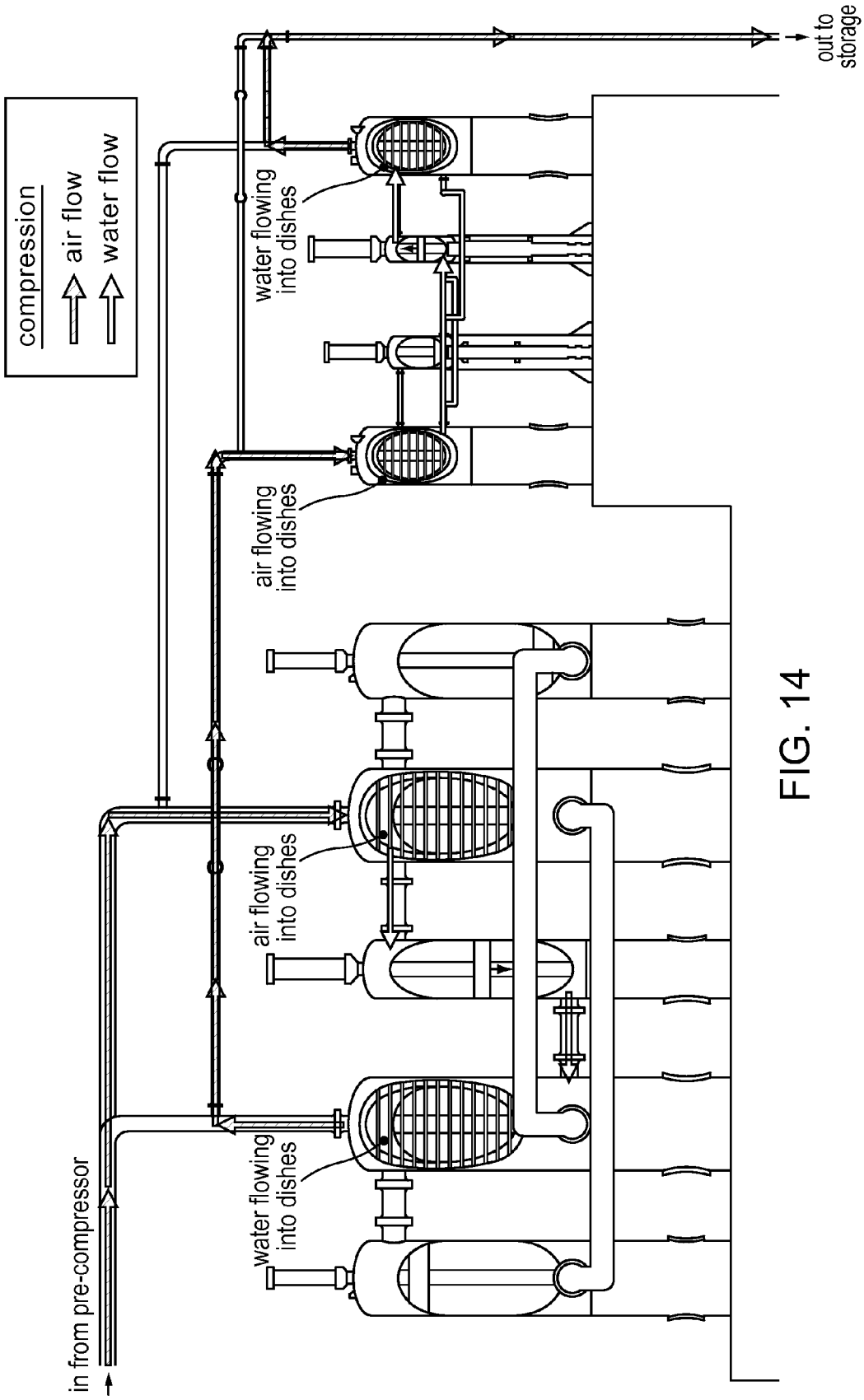

compression
air flow
water flow
in from pre-compressor
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
out to storage

FIG. 14

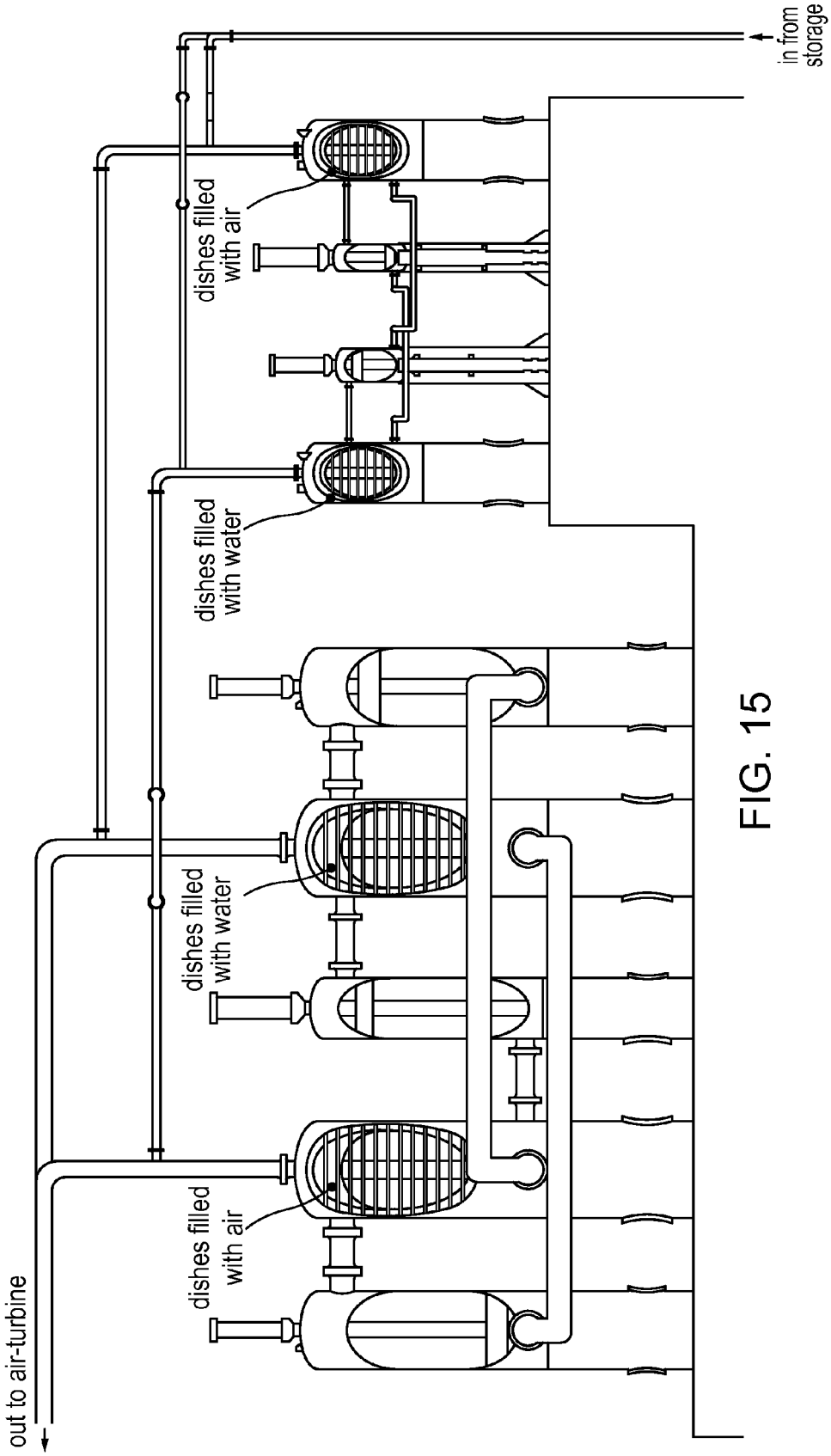

in from storage
dishes filled with air
dishes filled with water
dishes filled with water
dishes filled with air
out to air-turbine

FIG. 15

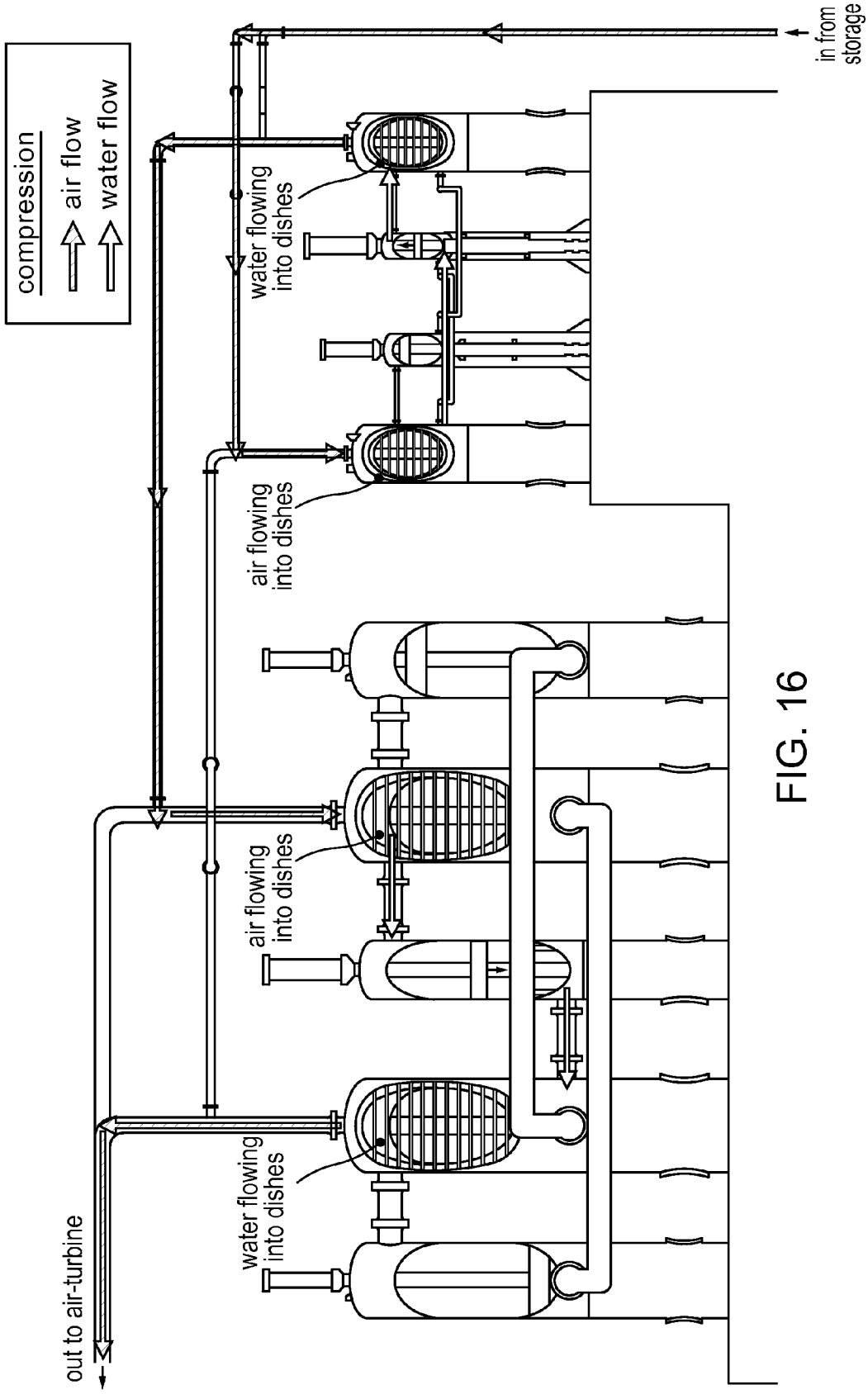

compression
air flow
water flow
in from storage
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
out to air-turbine

FIG. 16

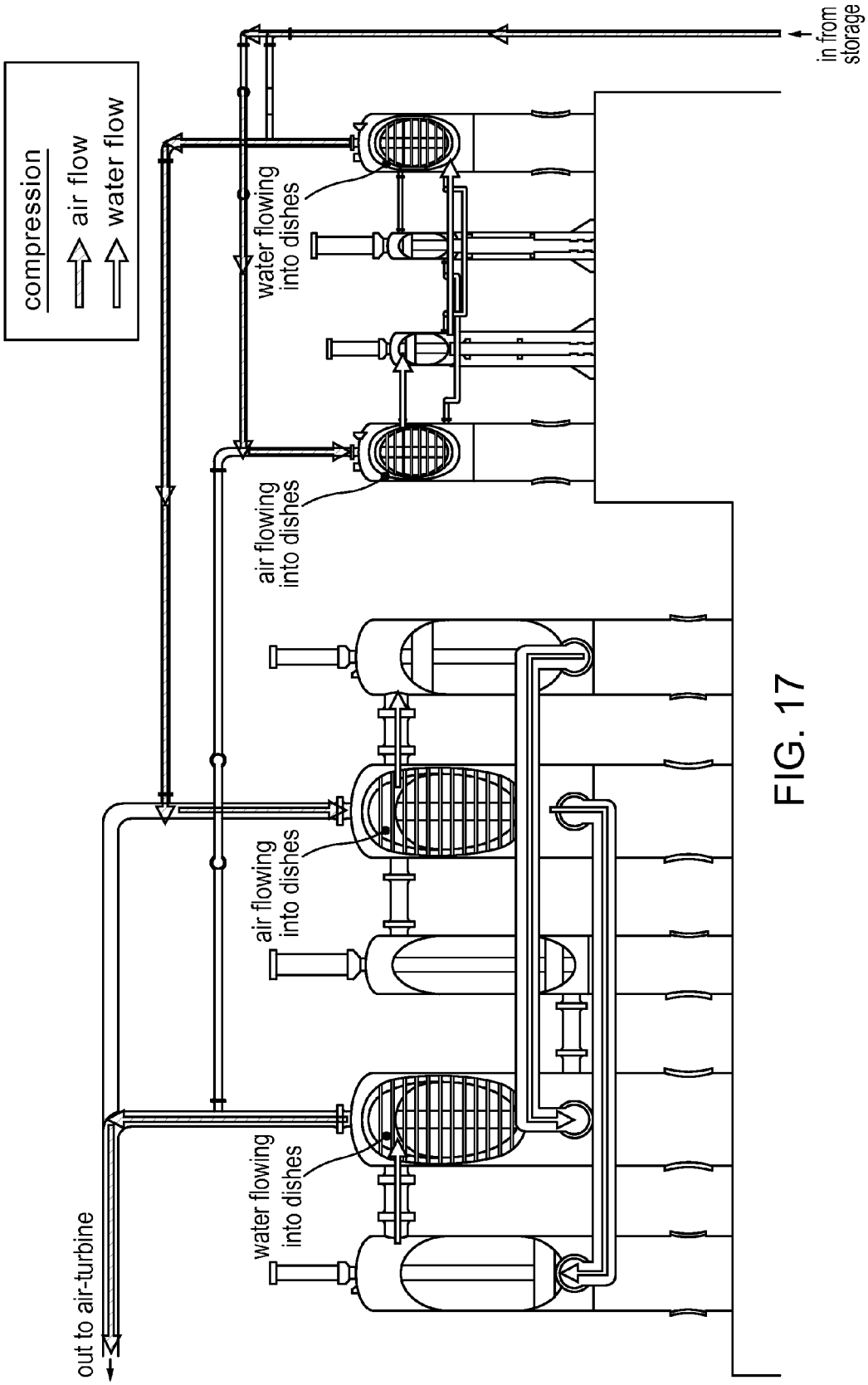

compression
air flow
water flow
in from storage
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
out to air-turbine

FIG. 17

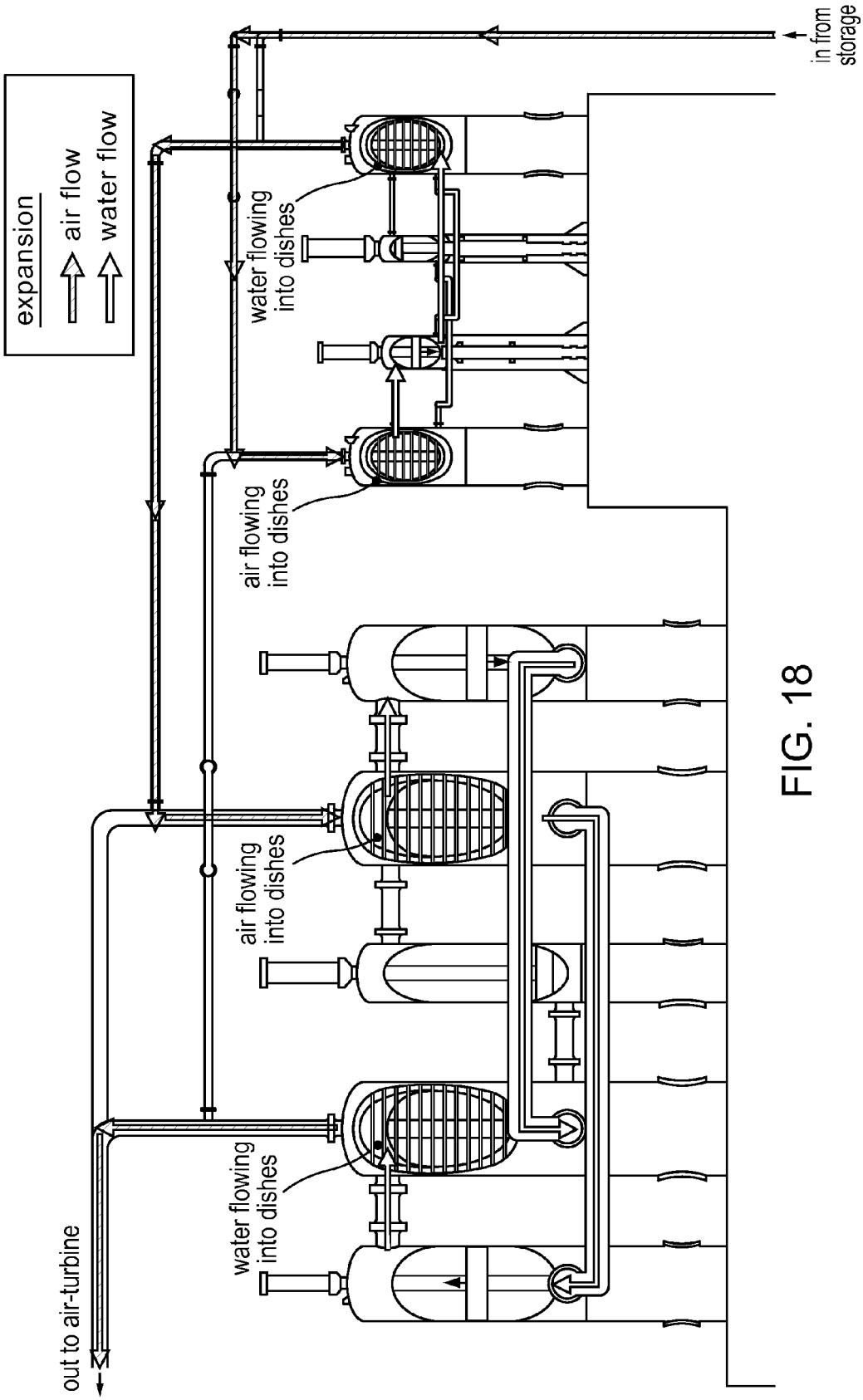

expansion
air flow
water flow
in from storage
water flowing into dishes
air flowing into dishes
air flowing into dishes
water flowing into dishes
out to air-turbine

FIG. 18

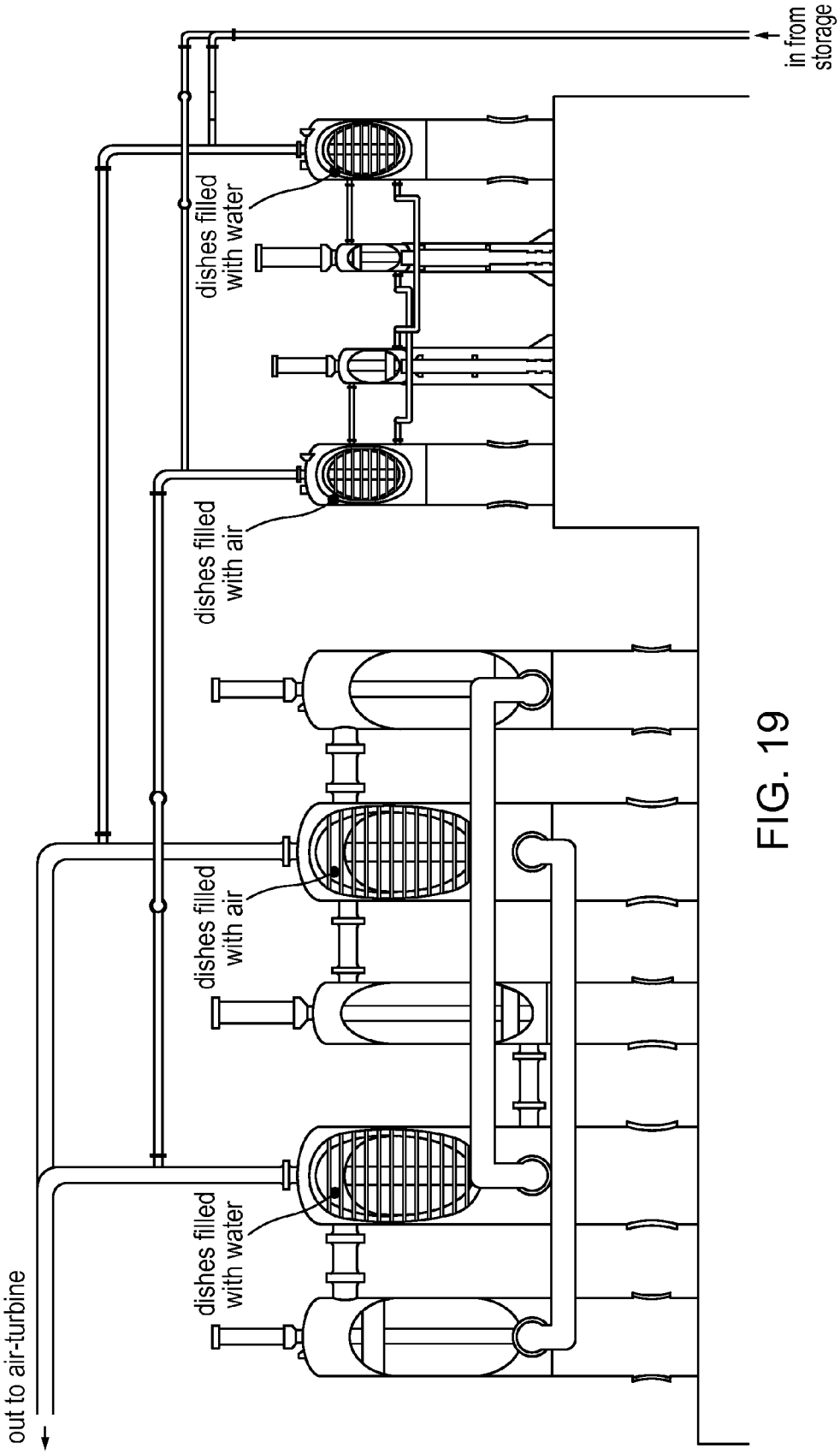

in from storage
dishes filled with water
dishes filled with air
dishes filled with air
dishes filled with water
out to air-turbine

FIG. 19

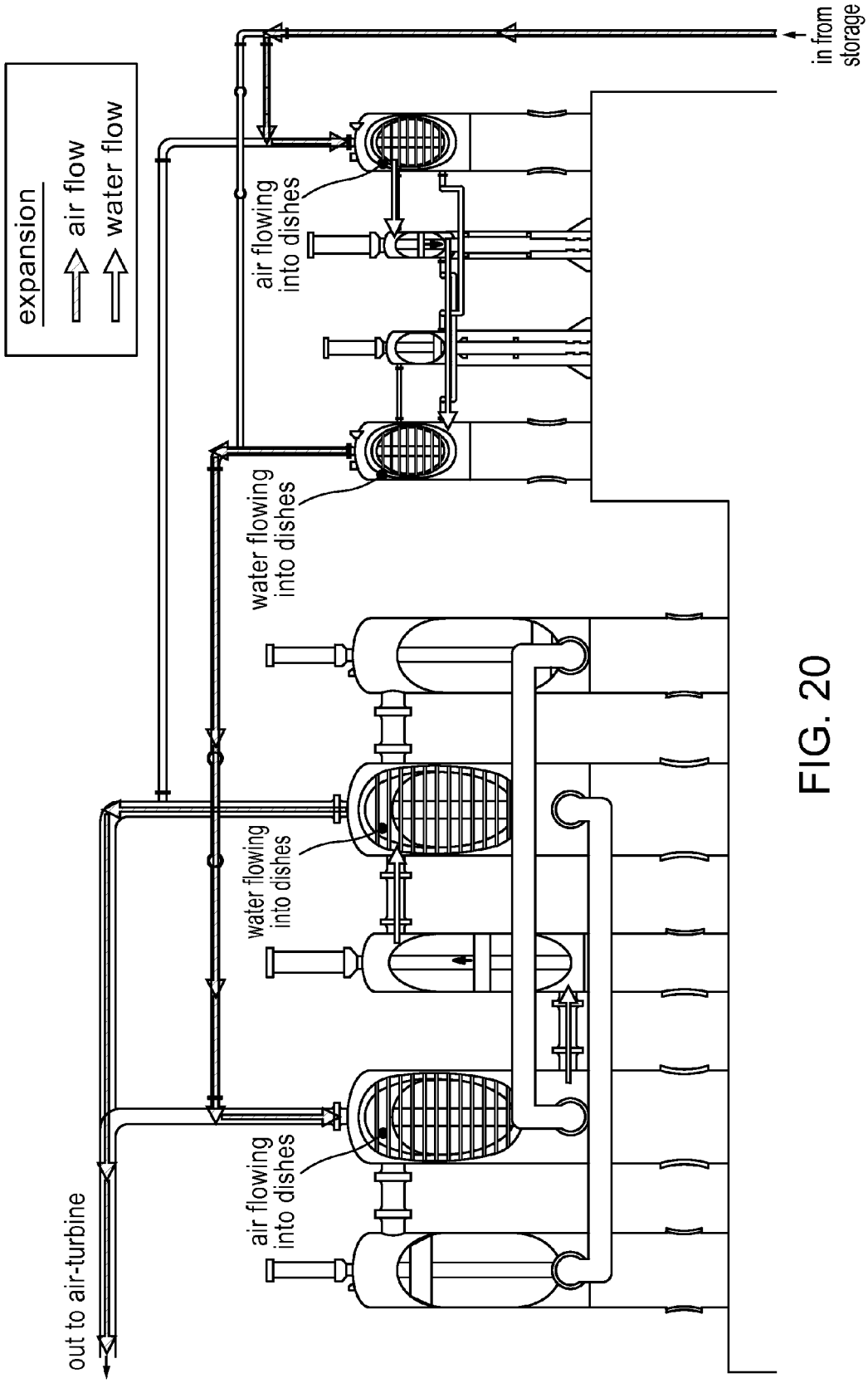

expansion
air flow
water flow
in from storage
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to air-turbine

FIG. 20

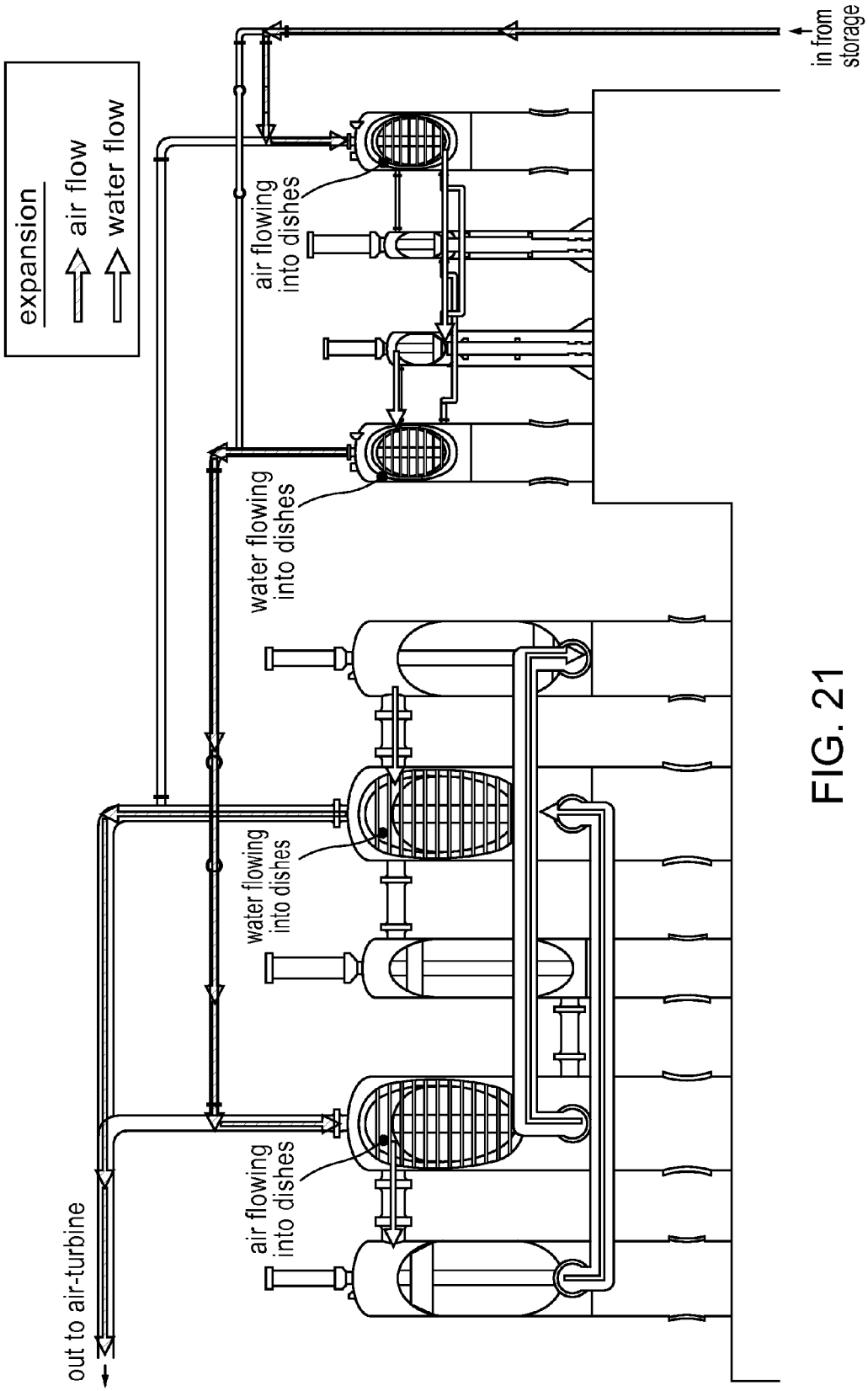

expansion
air flow
water flow
in from storage
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to air-turbine

FIG. 21

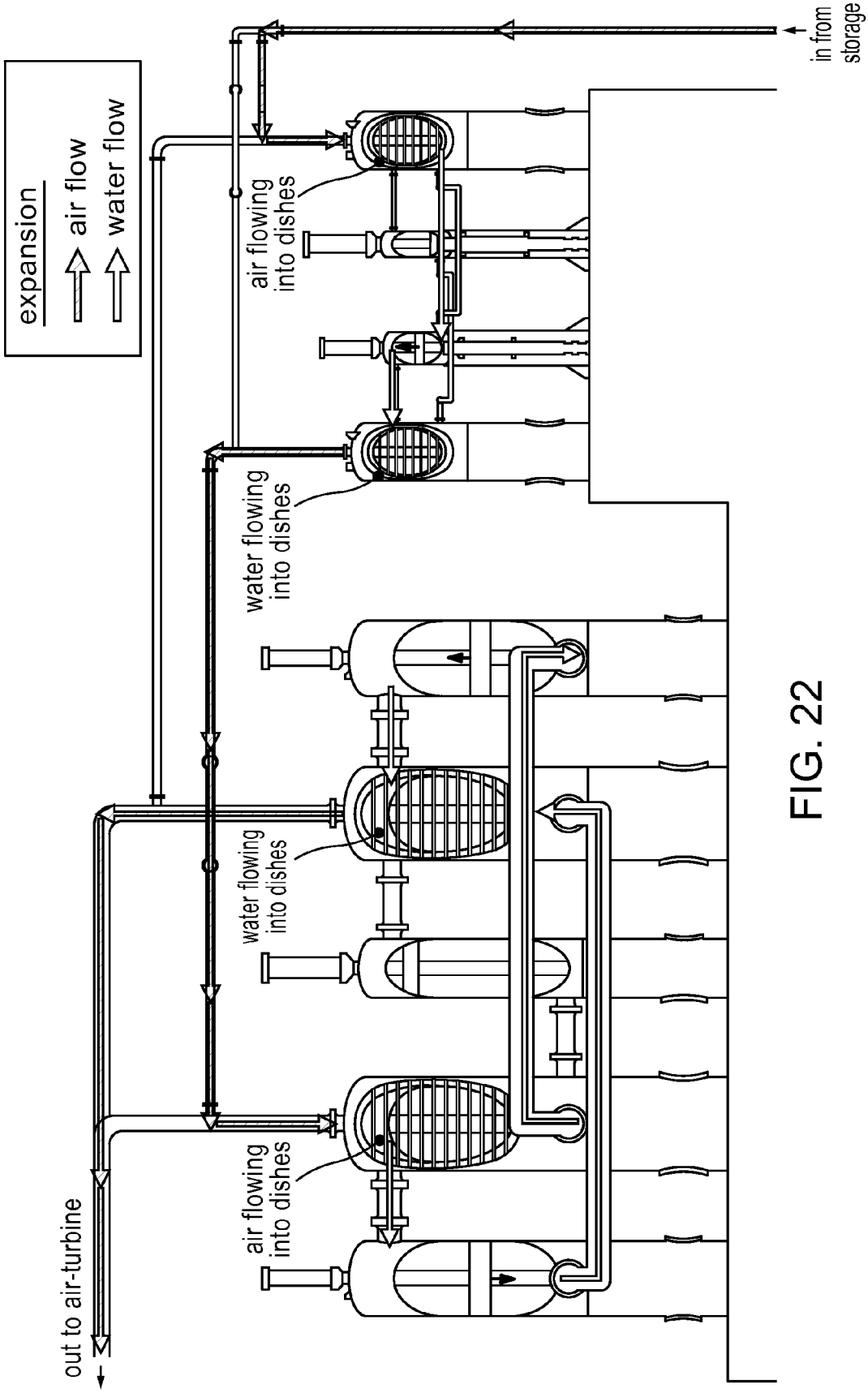

expansion
air flow
water flow
in from storage
air flowing into dishes
water flowing into dishes
water flowing into dishes
air flowing into dishes
out to air-turbine

FIG. 22

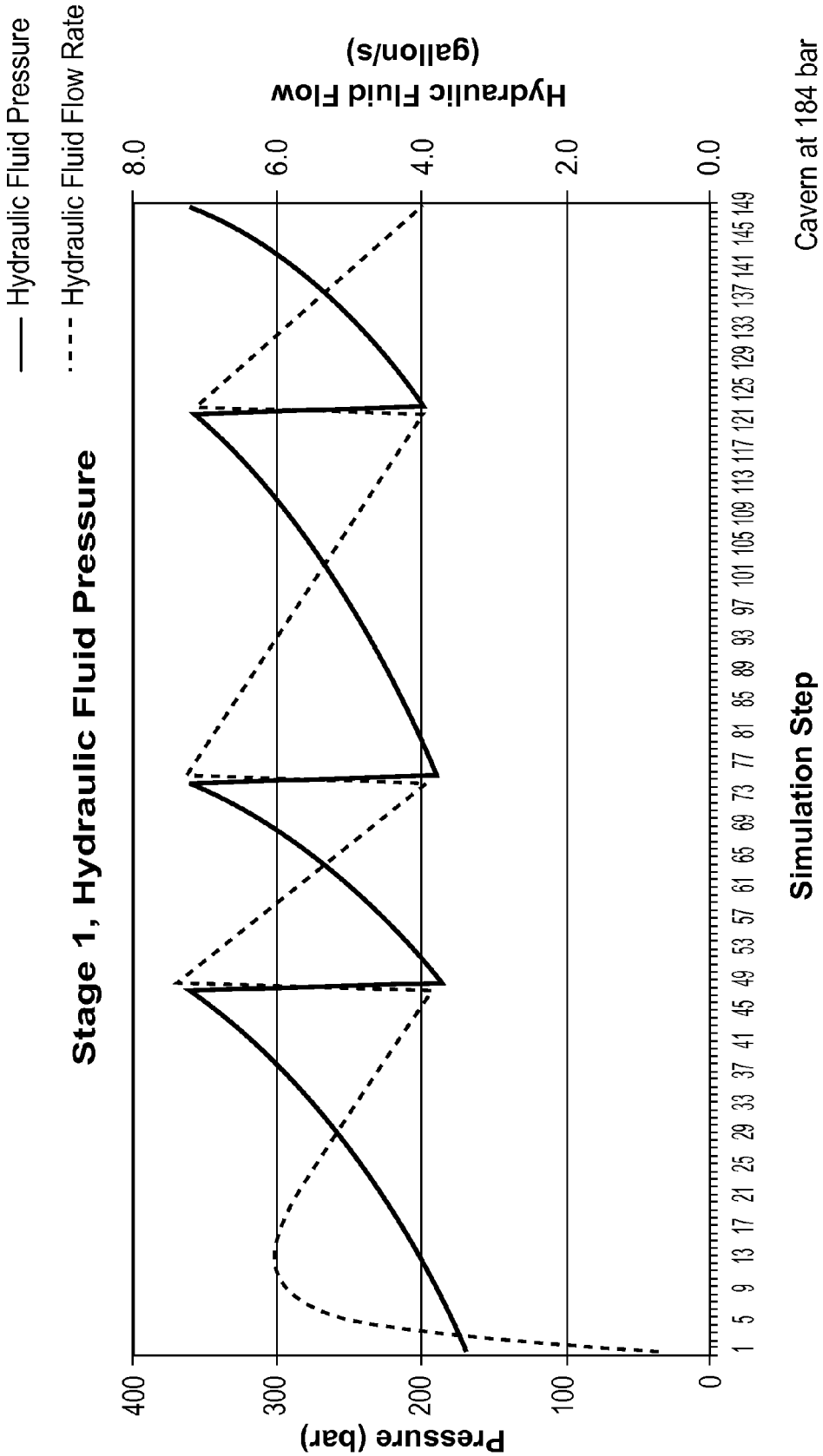

Stage 1, Hydraulic Fluid Pressure
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
8.0
6.0
4.0
2.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Cavern at 184 bar

FIG. 23

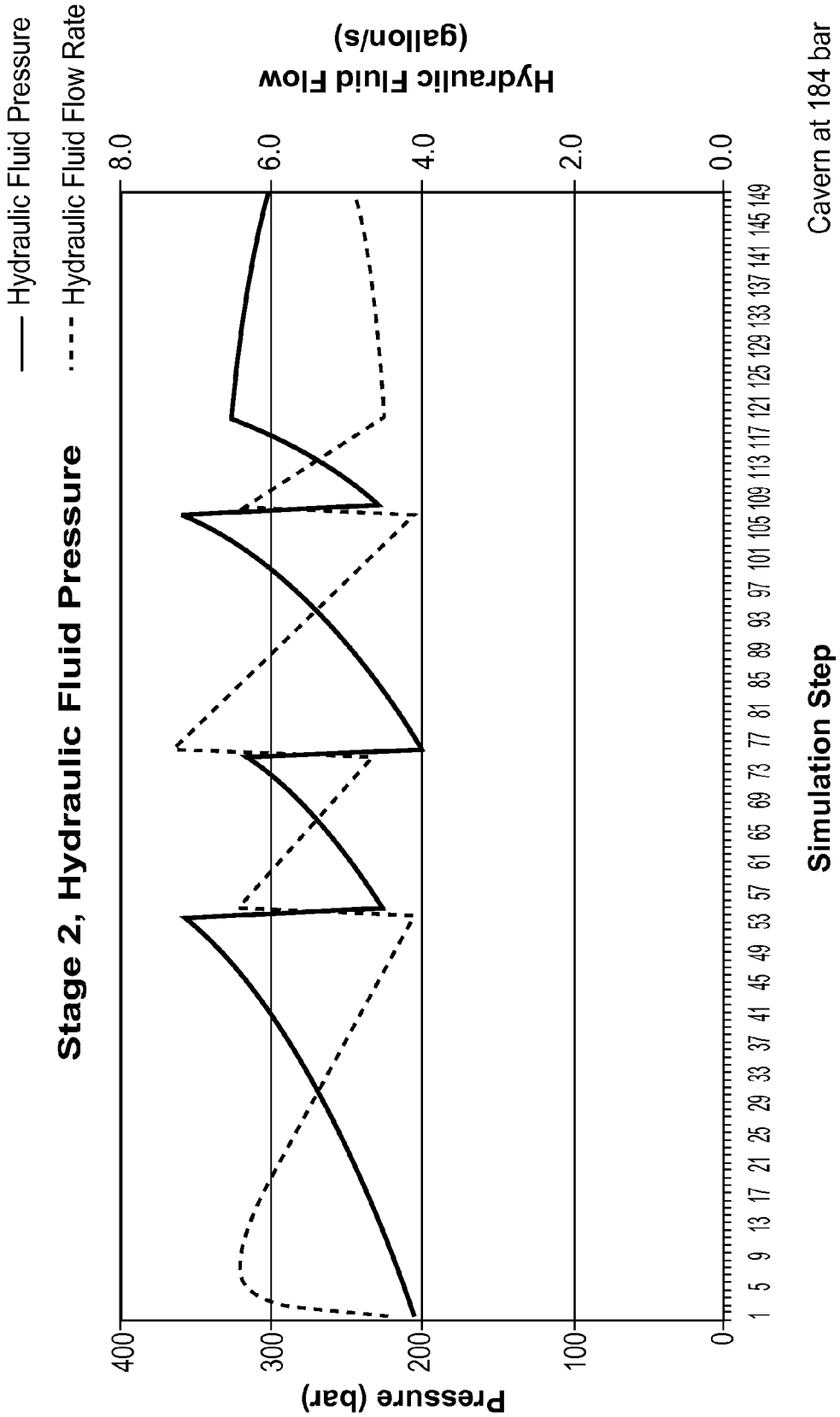

Stage 2, Hydraulic Fluid Pressure
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
8.0
6.0
4.0
2.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Cavern at 184 bar

FIG. 24

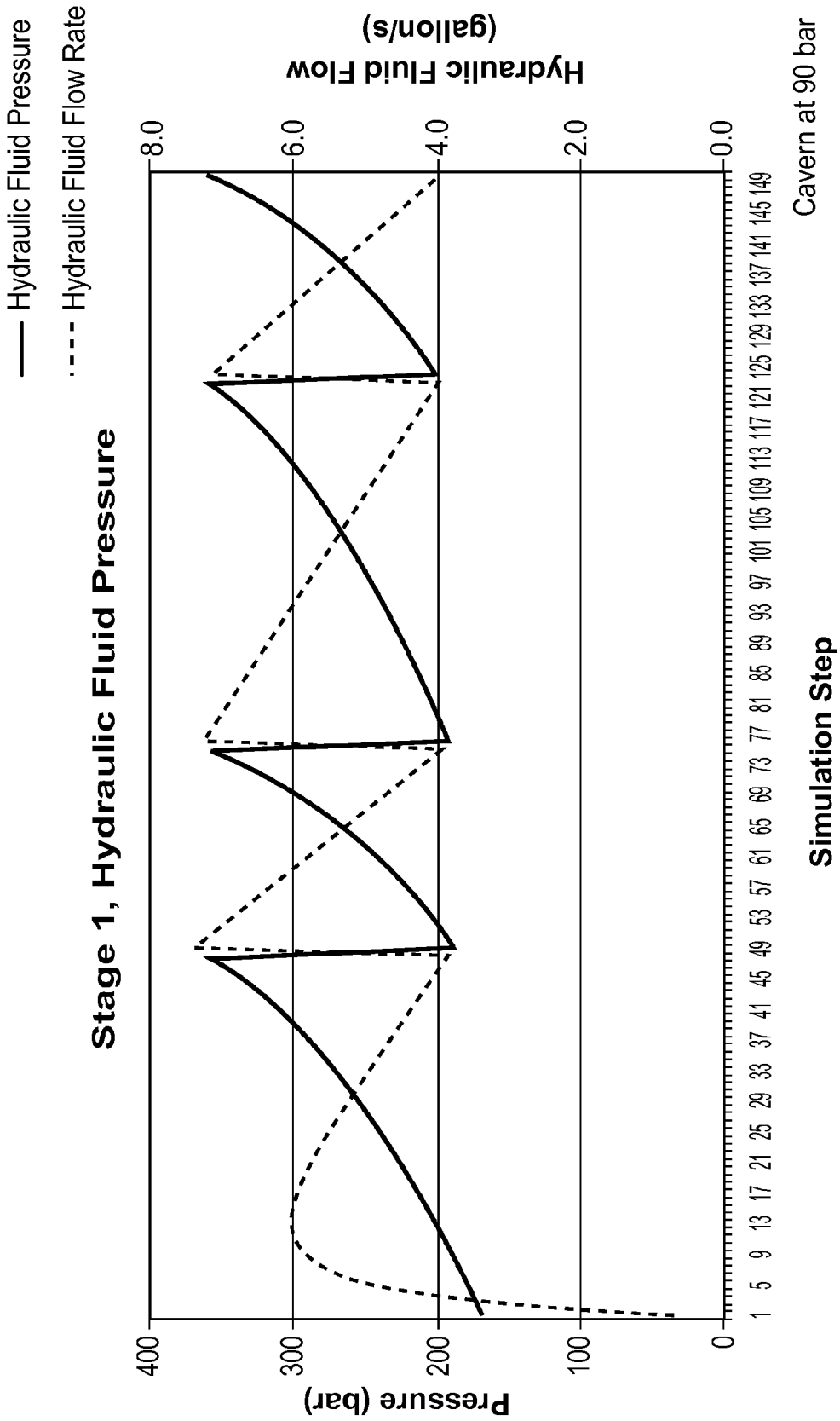

Stage 1, Hydraulic Fluid Pressure
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
8.0
6.0
4.0
2.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Cavern at 90 bar

FIG. 25

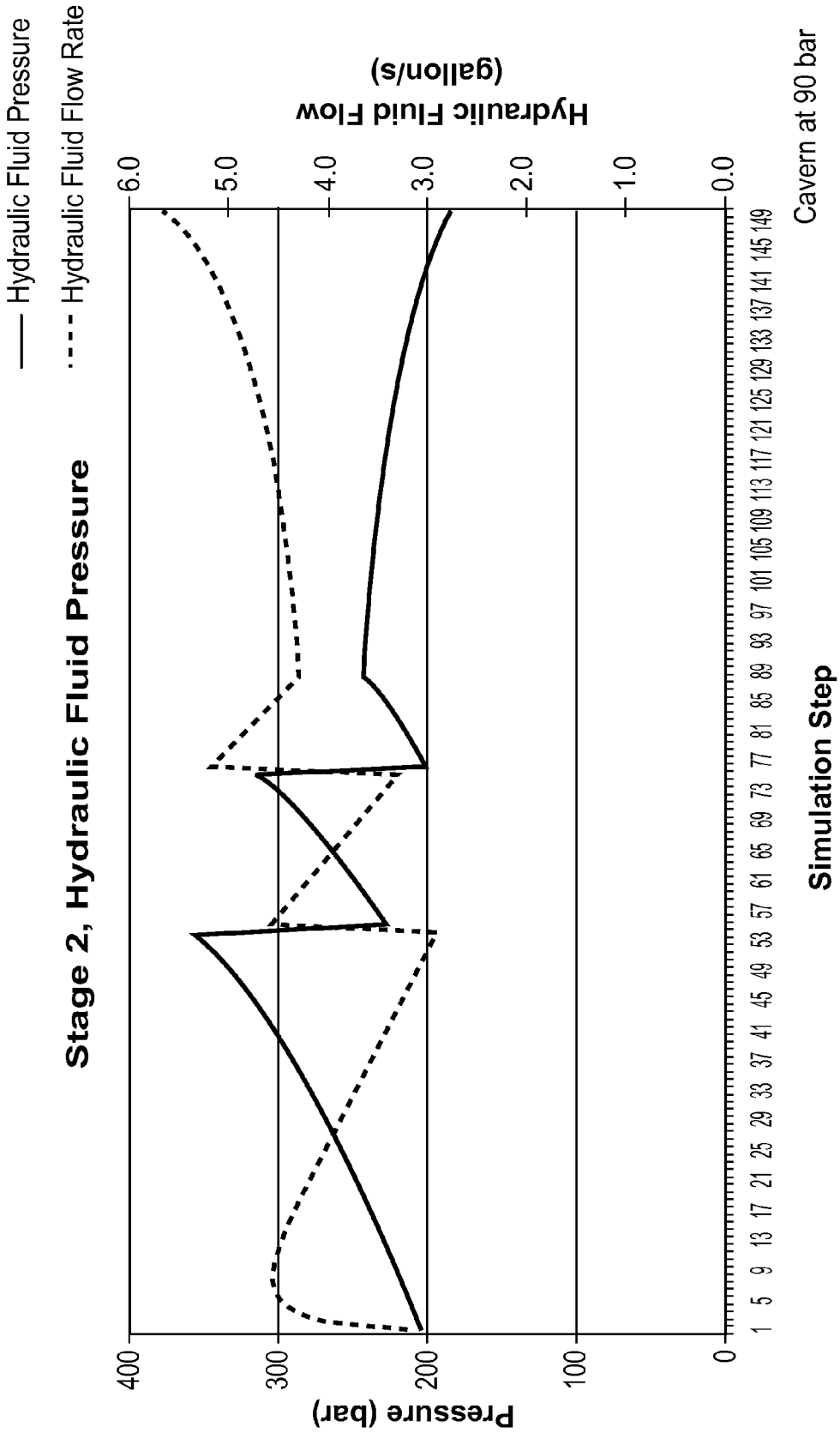
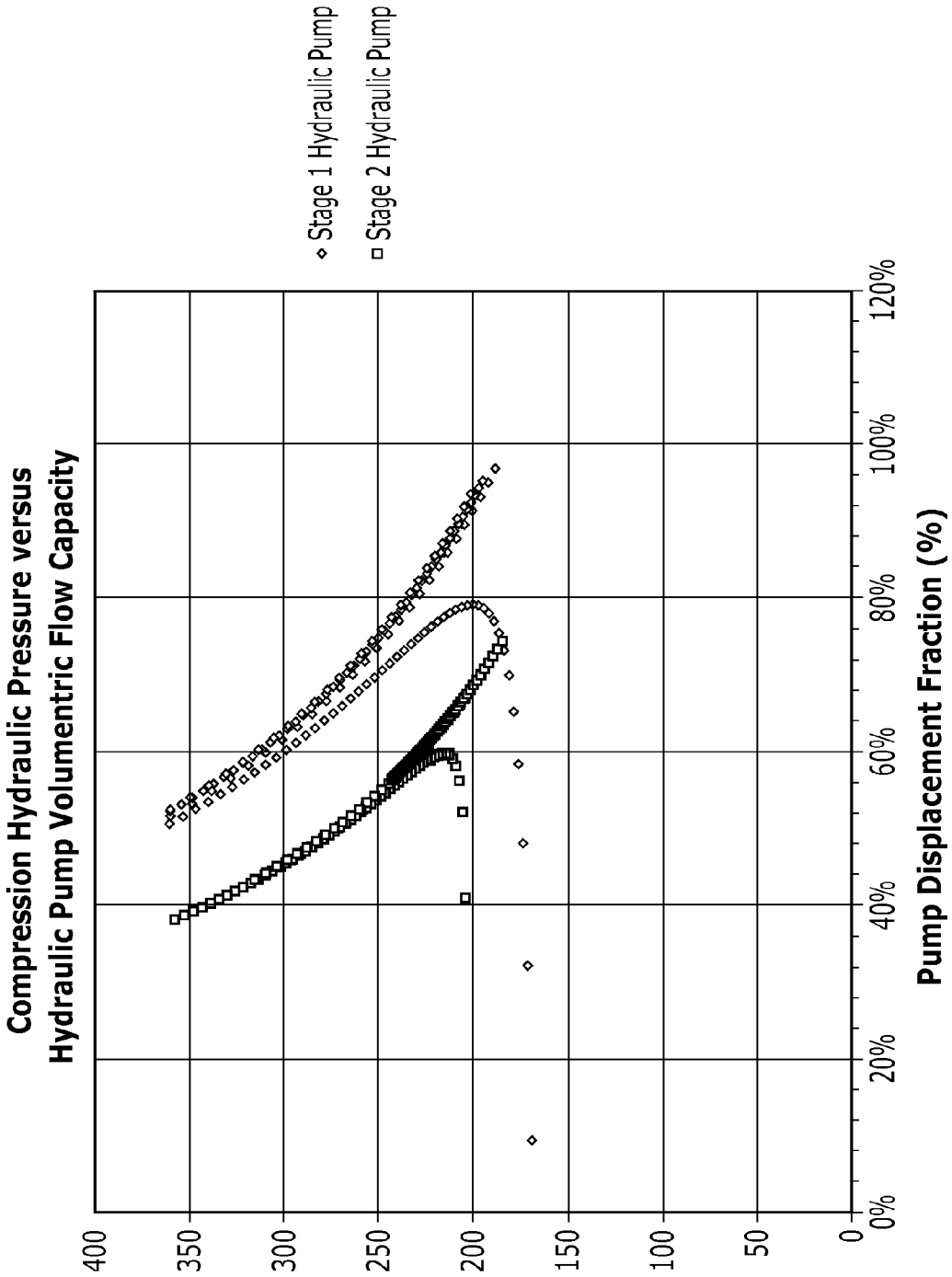
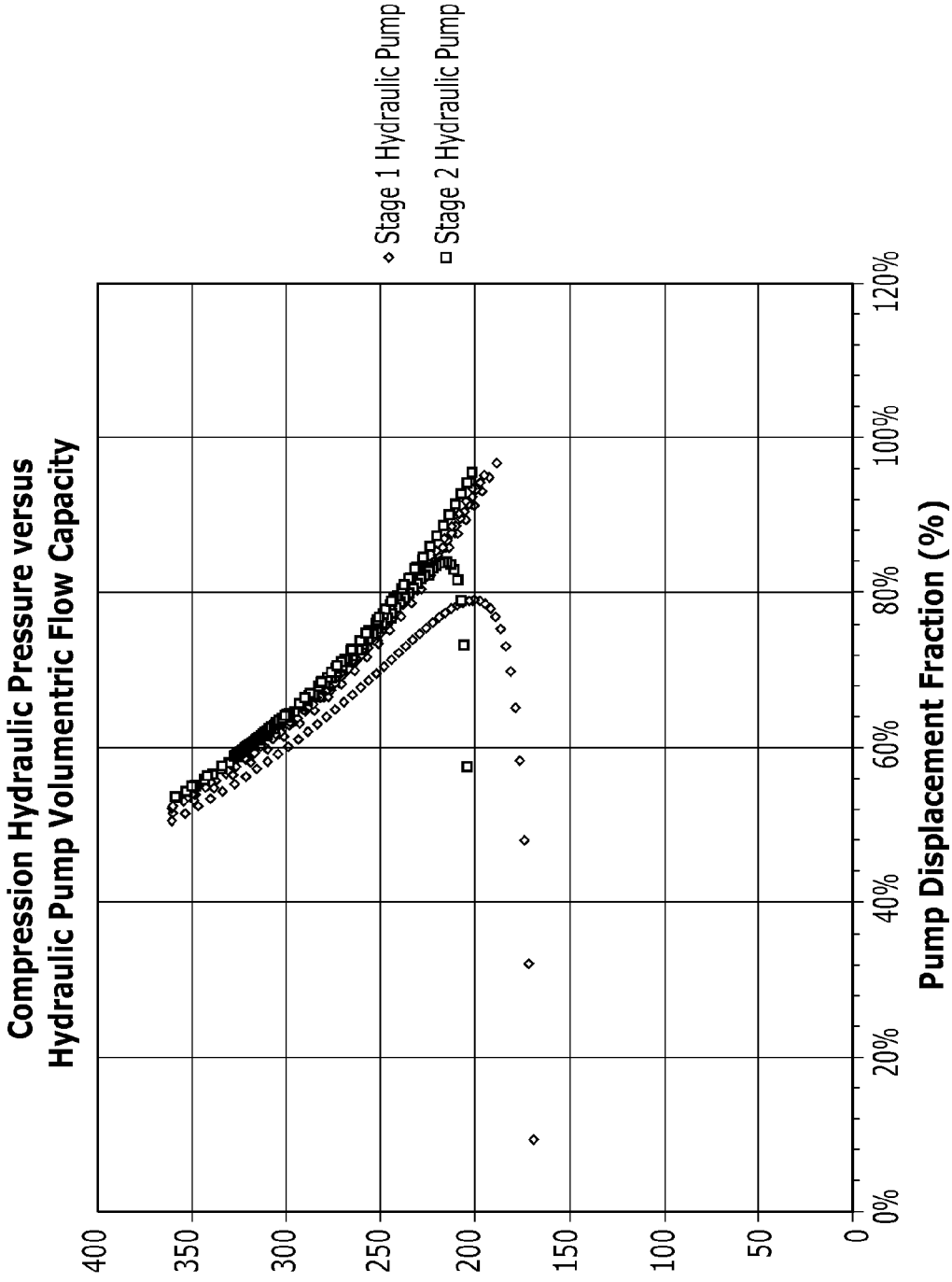

Stage 2, Hydraulic Fluid Pressure
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Cavern at 90 bar

FIG. 26



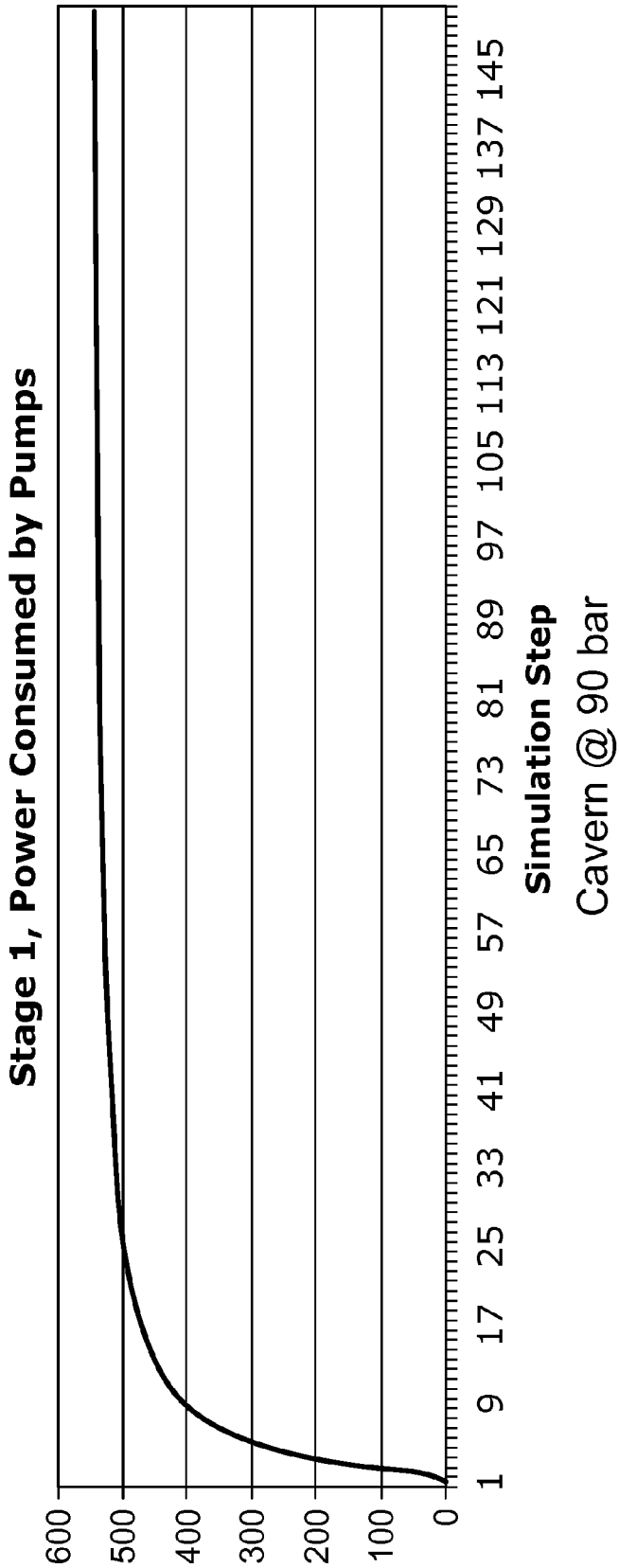
Cavern @ 90 bar

FIG. 27



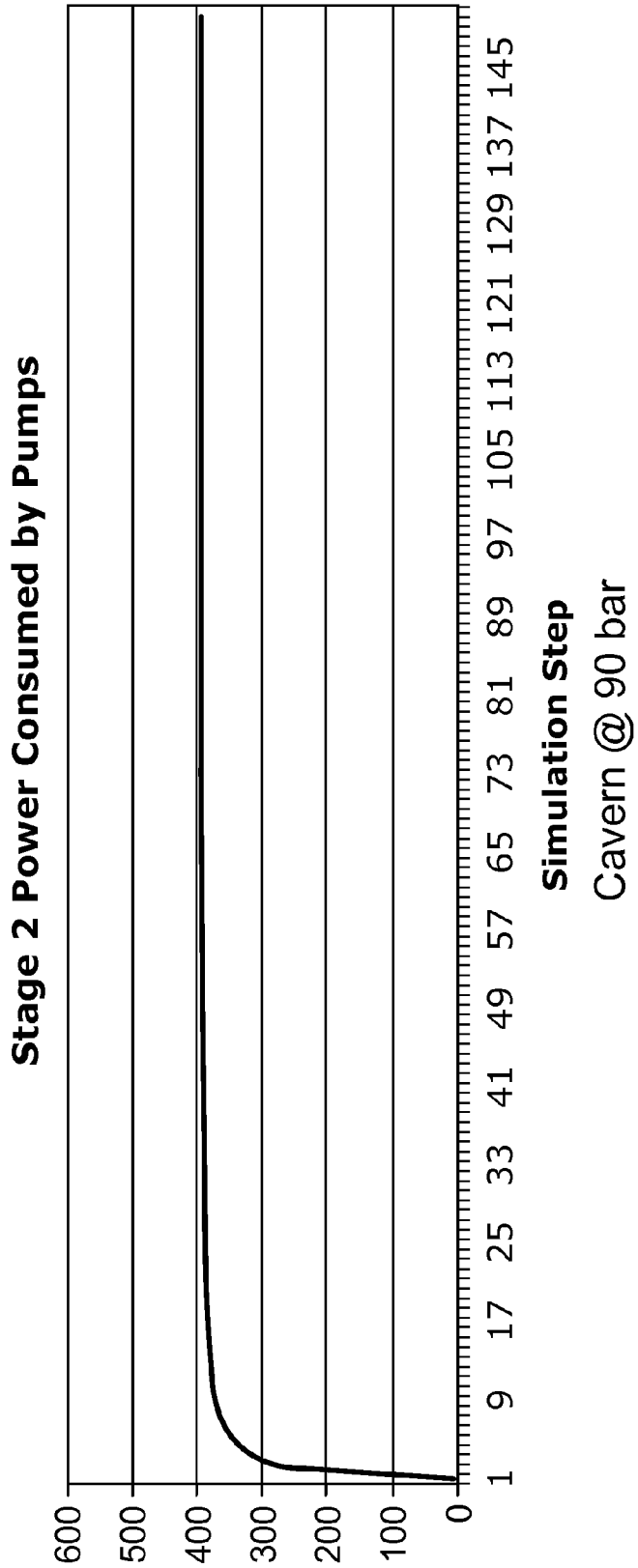
Cavern @ 180 bar

FIG. 28



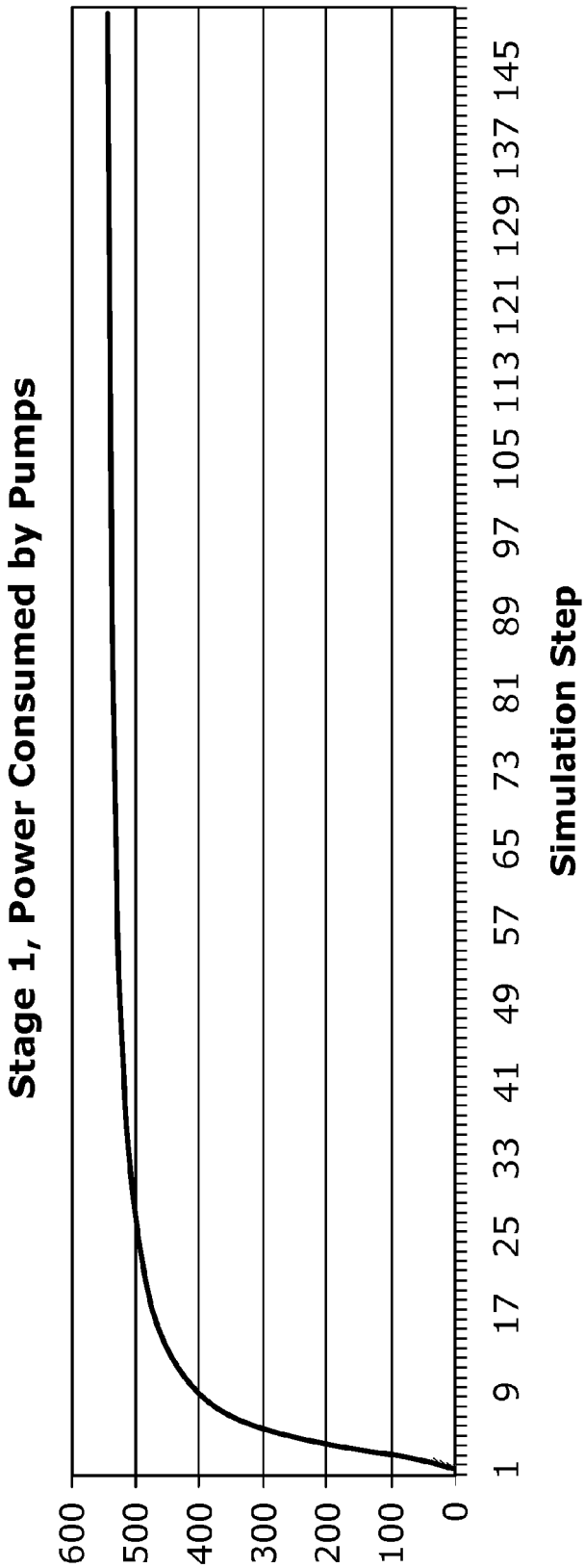
Cavern @ 90 bar

FIG. 29



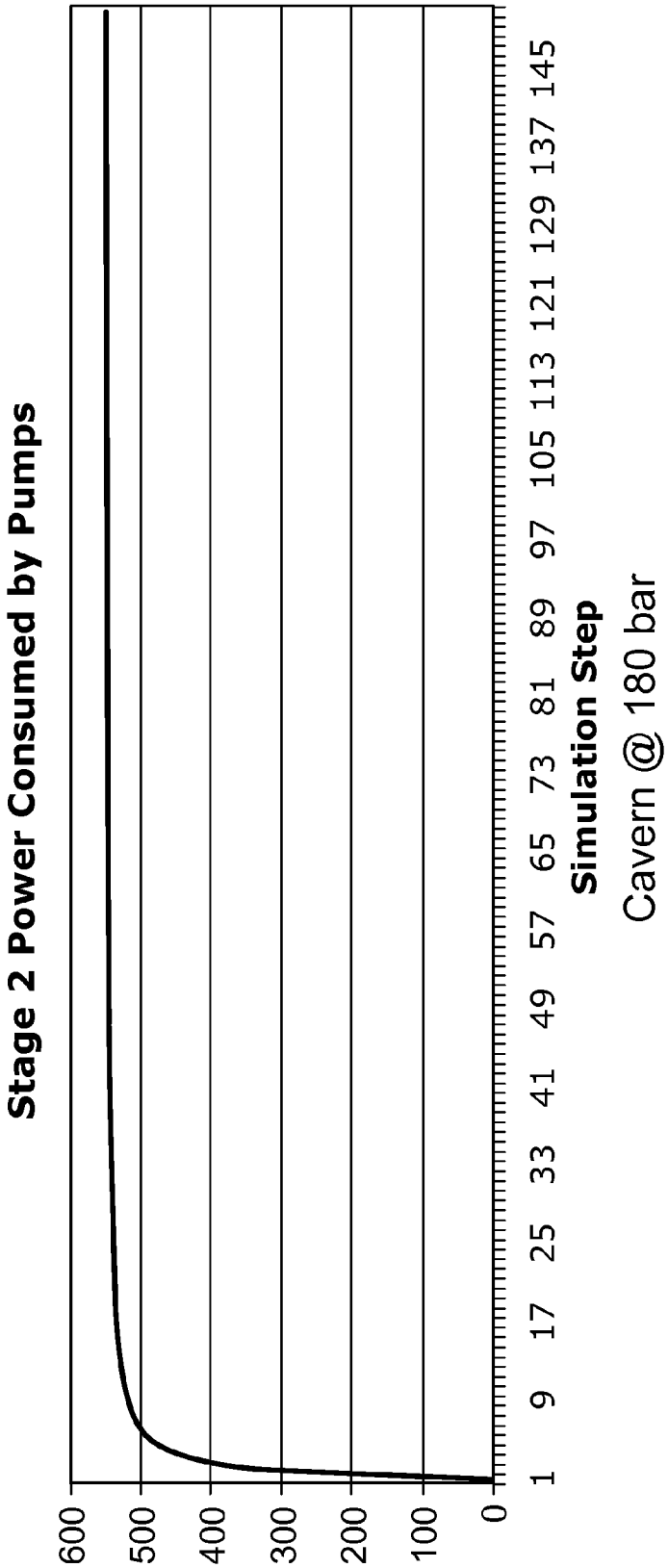
Cavern @ 90 bar

FIG. 30



Cavern @ 180 bar

FIG. 31



Cavern @ 180 bar

FIG. 32

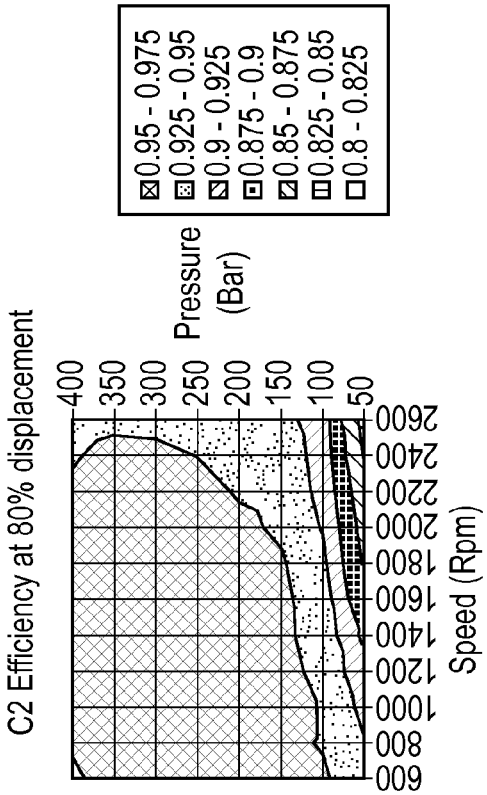

C2 Efficiency at 80% displacement
Pressure (Bar)
400
350
300
250
200
150
100
50
Speed (Rpm)
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
0.95 - 0.975
0.925 - 0.95
0.9 - 0.925
0.875 - 0.9
0.85 - 0.875
0.825 - 0.85
0.8 - 0.825

FIG.34

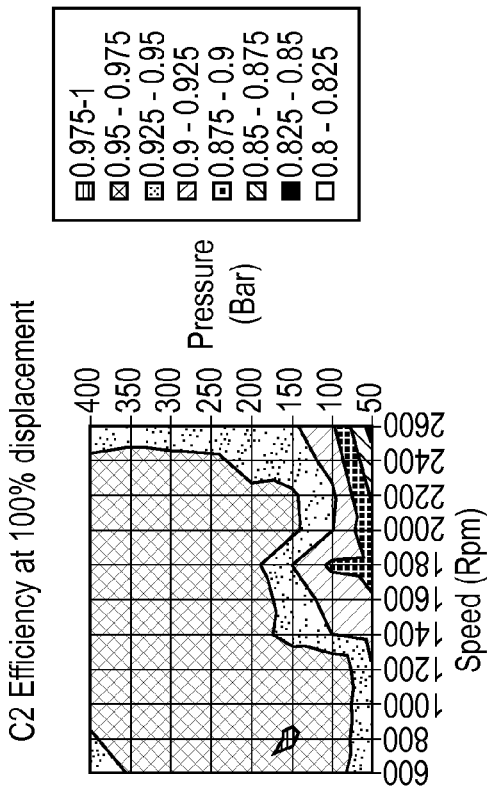

C2 Efficiency at 100% displacement
Pressure (Bar)
400
350
300
250
200
150
100
50
Speed (Rpm)
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
0.975-1
0.95 - 0.975
0.925 - 0.95
0.9 - 0.925
0.875 - 0.9
0.85 - 0.875
0.825 - 0.85
0.8 - 0.825

FIG.33

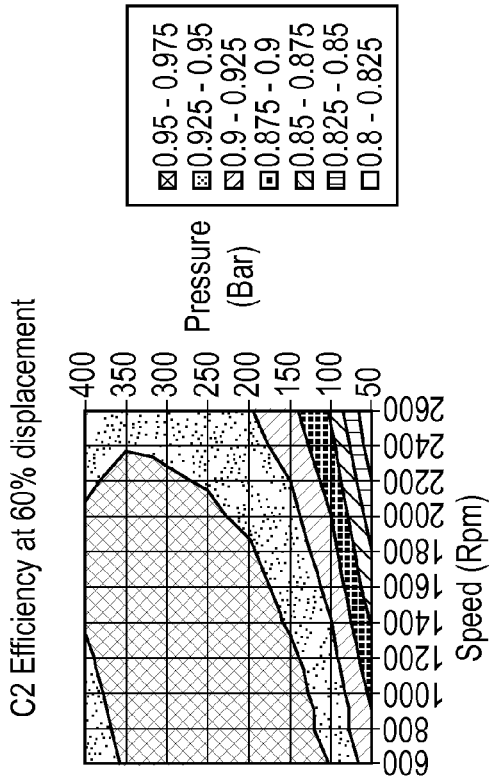

C2 Efficiency at 60% displacement
Pressure (Bar)
400
350
300
250
200
150
100
50
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Speed (Rpm)
0.95 - 0.975
0.925 - 0.95
0.9 - 0.925
0.875 - 0.9
0.85 - 0.875
0.825 - 0.85
0.8 - 0.825

FIG.35

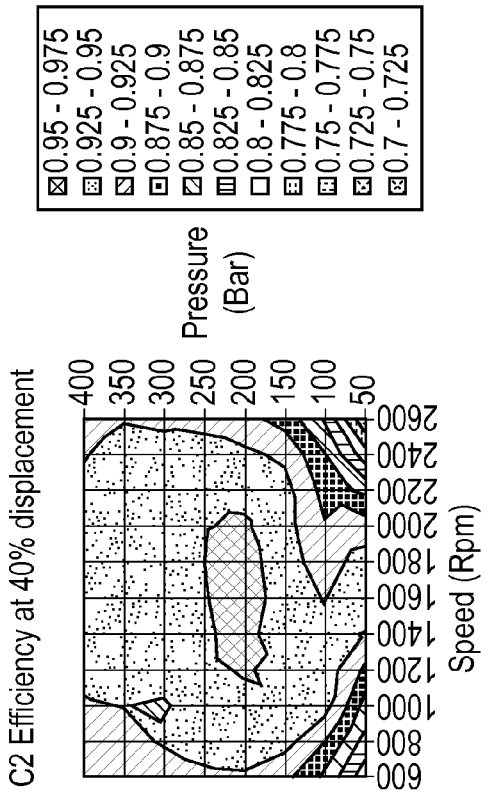

C2 Efficiency at 40% displacement
Pressure (Bar)
400
350
300
250
200
150
100
50
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Speed (Rpm)
0.95 - 0.975
0.925 - 0.95
0.9 - 0.925
0.875 - 0.9
0.85 - 0.875
0.825 - 0.85
0.8 - 0.825
0.775 - 0.8
0.75 - 0.775
0.725 - 0.75
0.7 - 0.725

FIG.36

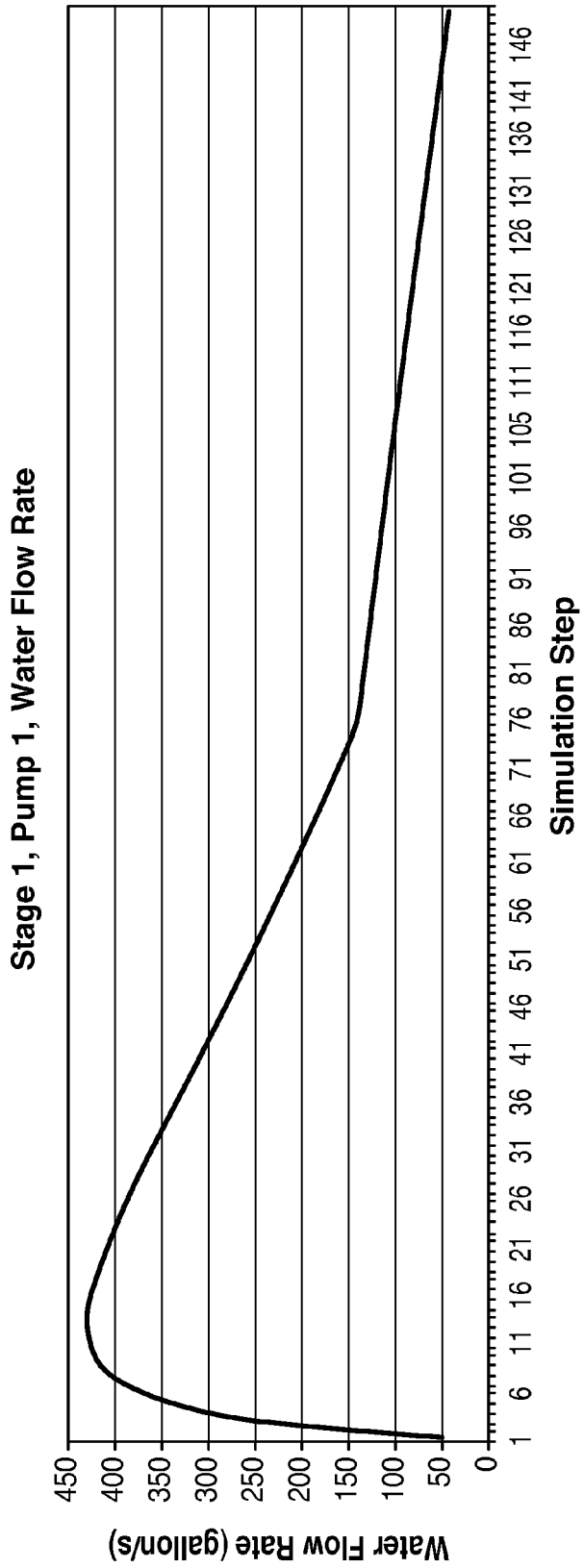

Stage 1, Pump 1, Water Flow Rate
Water Flow Rate (gallon/s)
450
400
350
300
250
200
150
100
50
0
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96 101 105 111 116 121 126 131 136 141 146
Simulation Step

FIG. 37

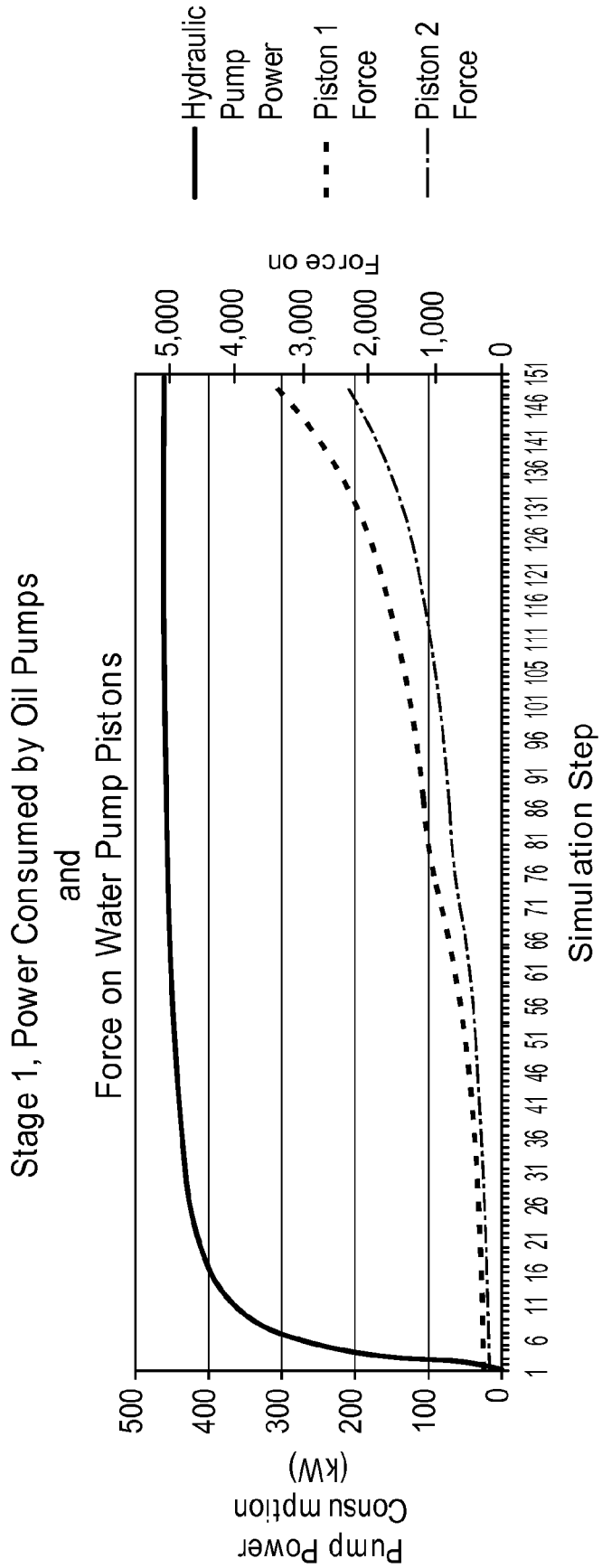

Stage 1, Power Consumed by Oil Pumps
and
Force on Water Pump Pistons
Pump Power Consumption (kW)
500
400
300
200
100
0
Force on
5,000
4,000
3,000
2,000
1,000
0
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96 101 105 111 116 121 126 131 136 141 146 151
Simulation Step
Hydraulic Pump Power
Piston 1 Force
Piston 2 Force

FIG. 38

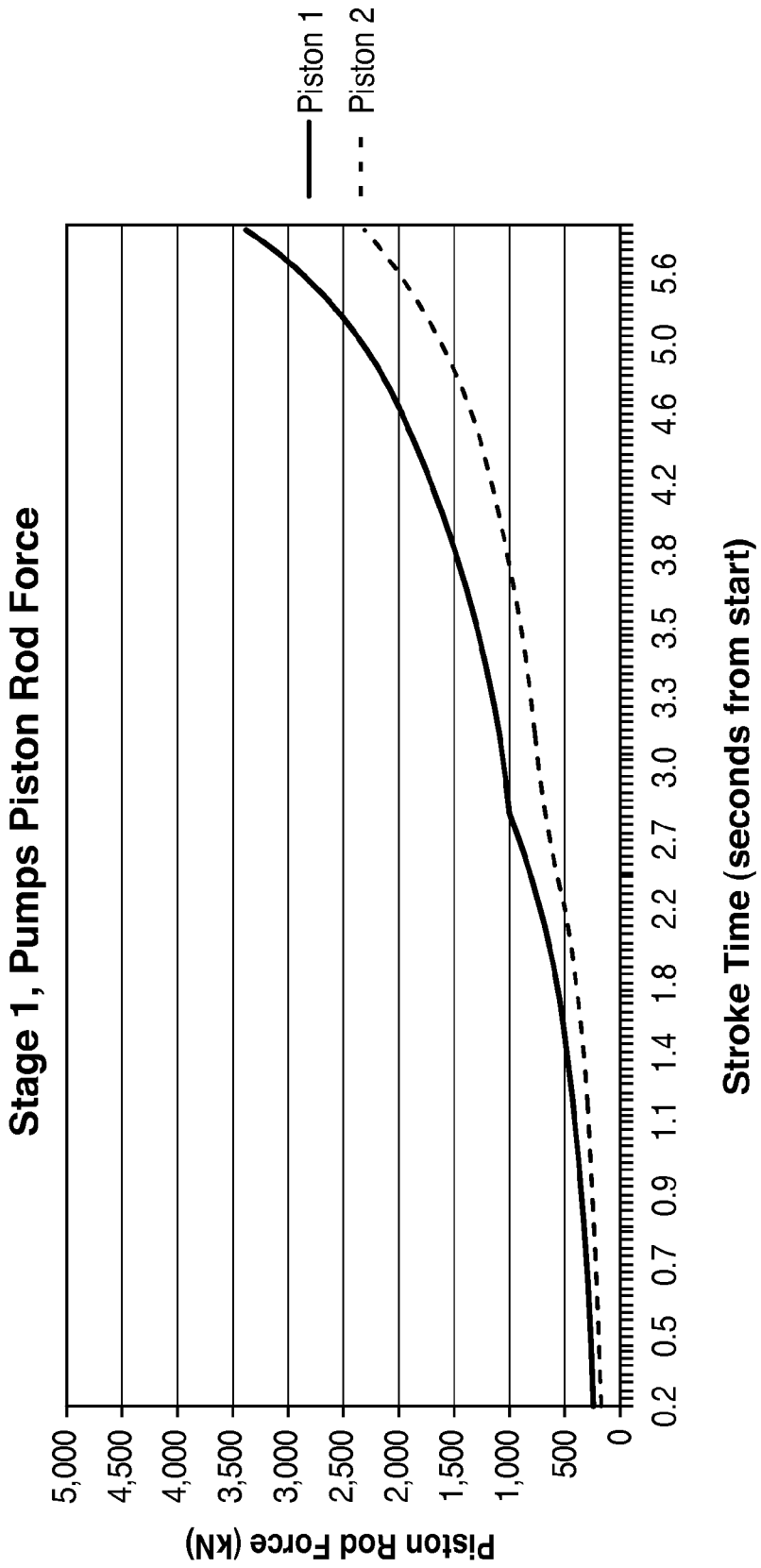

Stage 1, Pumps Piston Rod Force
Piston 1
Piston 2
Piston Rod Force (kN)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0.2
0.5
0.7
0.9
1.1
1.4
1.8
2.2
2.7
3.0
3.3
3.5
3.8
4.2
4.6
5.0
5.6
Stroke Time (seconds from start)

FIG. 39

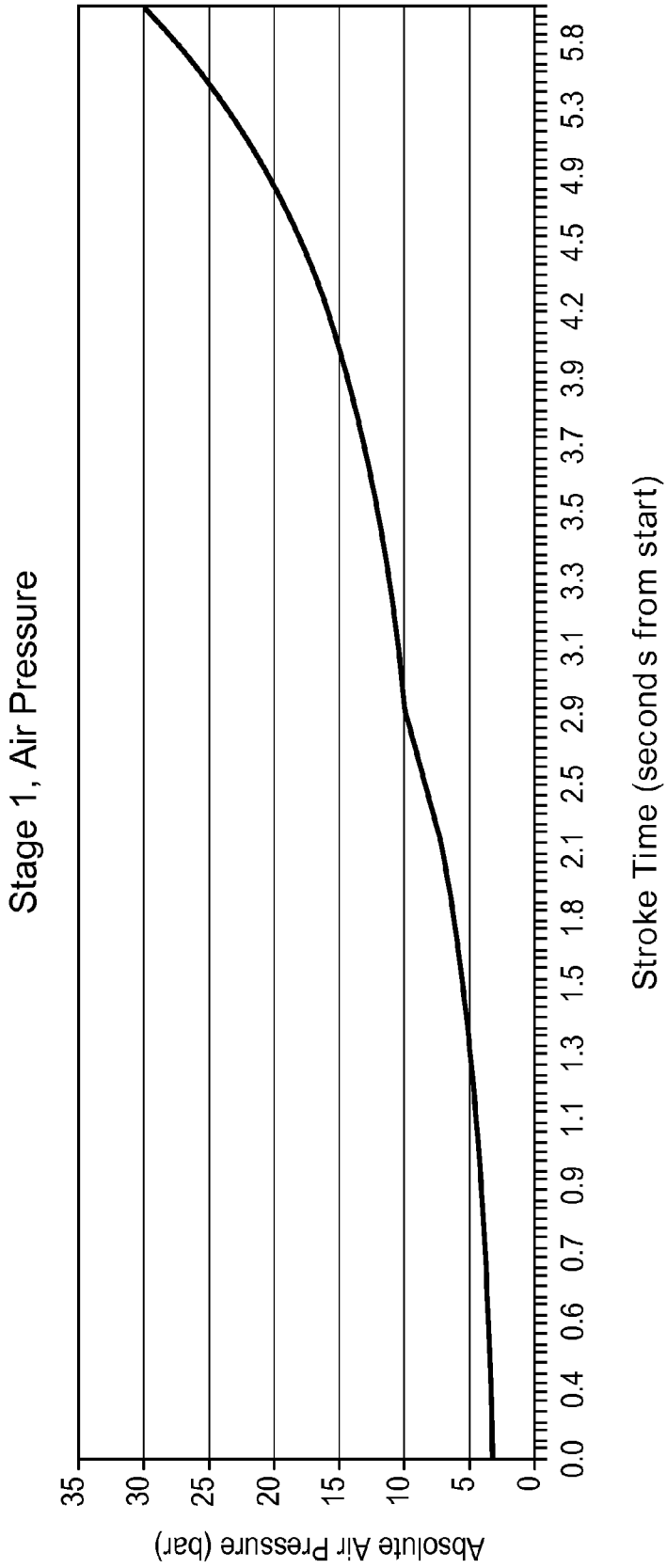

Stage 1, Air Pressure
Absolute Air Pressure (bar)
35
30
25
20
15
10
5
0
0.0 0.4 0.6 0.7 0.9 1.1 1.3 1.5 1.8 2.1 2.5 2.9 3.1 3.3 3.5 3.7 3.9 4.2 4.5 4.9 5.3 5.8
Stroke Time (seconds from start)

FIG. 40

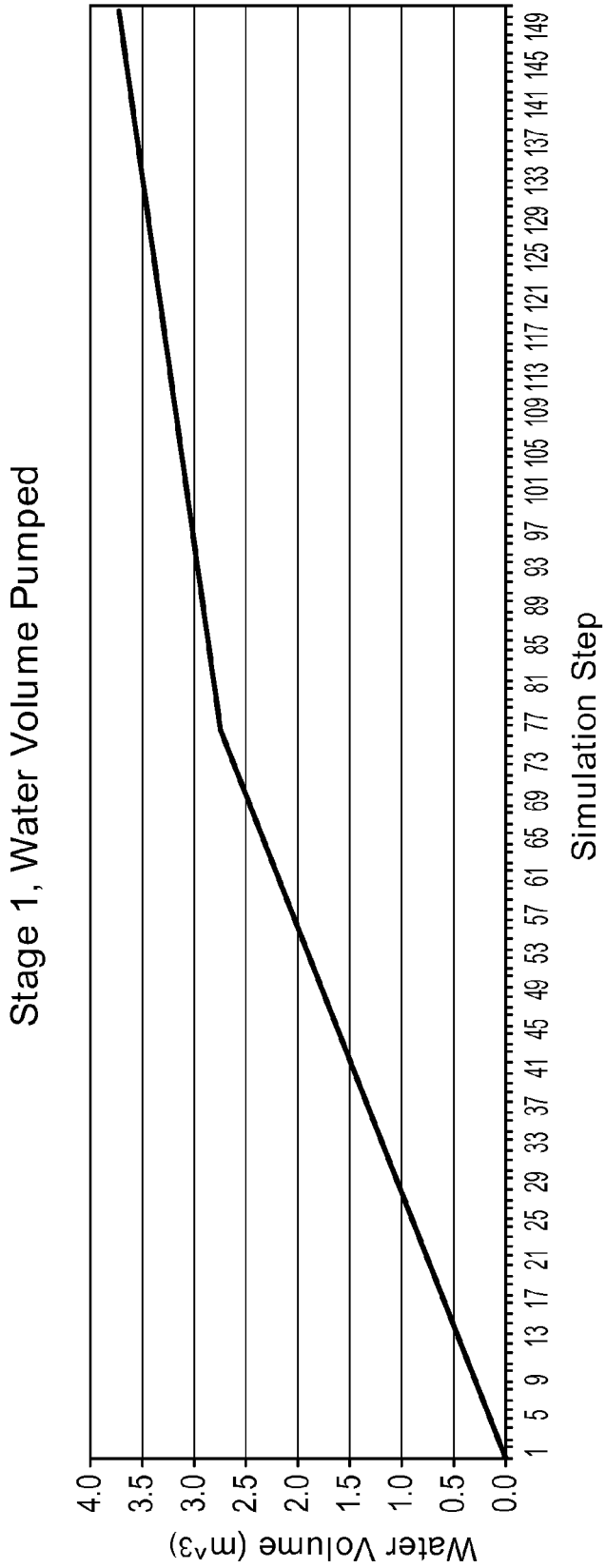

Stage 1, Water Volume Pumped
Water Volume (m^3)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step

FIG. 41

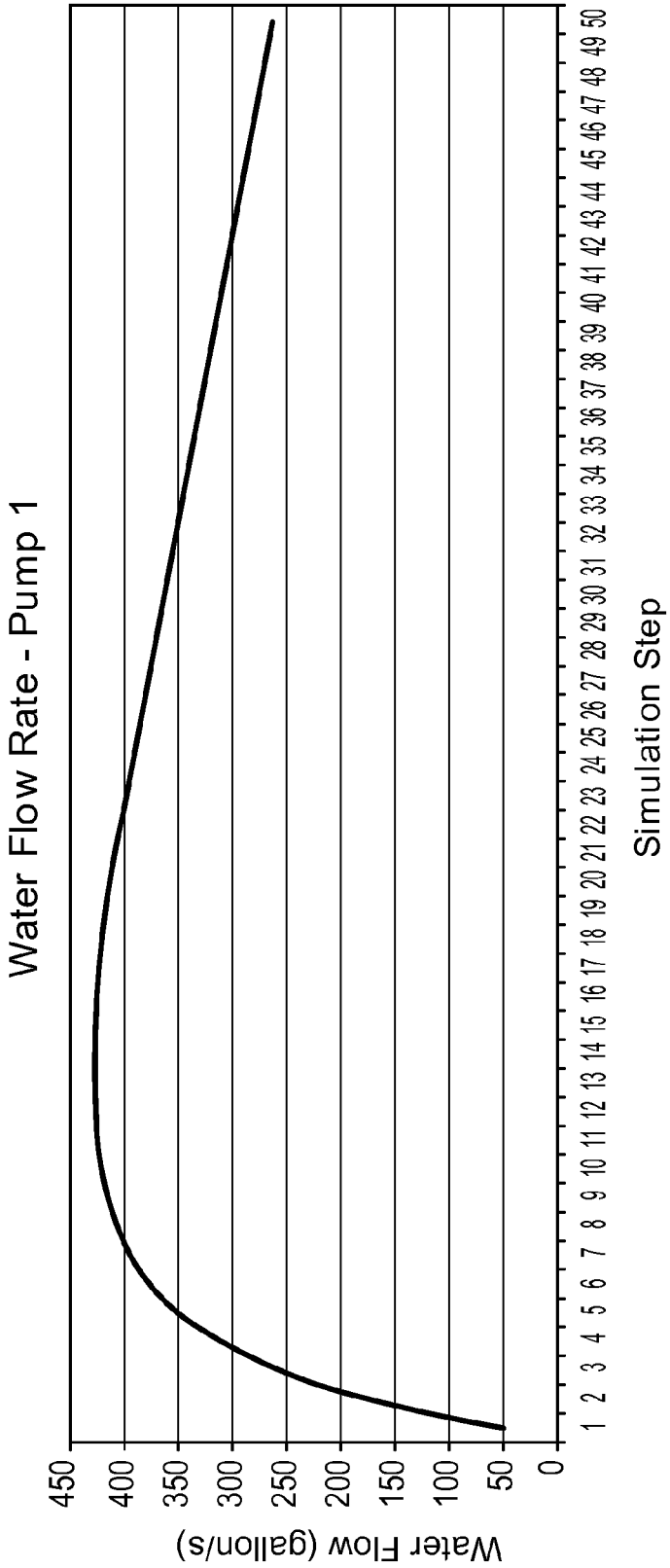

Water Flow Rate - Pump 1
Water Flow (gallon/s)
450
400
350
300
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
Simulation Step

FIG. 42

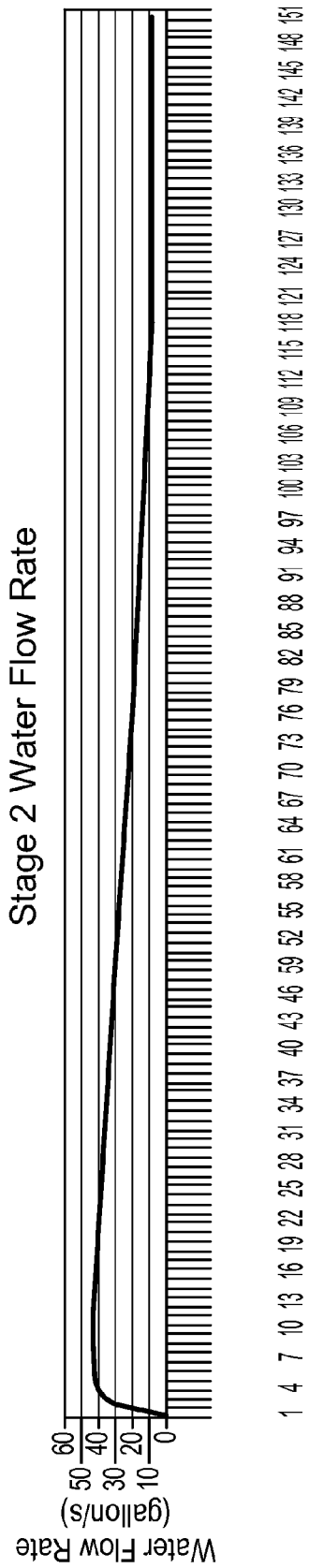

Stage 2 Water Flow Rate
Water Flow Rate (gallon/s)
60
50
40
30
20
10
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79 82 85 88 91 94 97 100 103 106 109 112 115 118 121 124 127 130 133 136 139 142 145 148 151
Simulation 1

FIG. 43

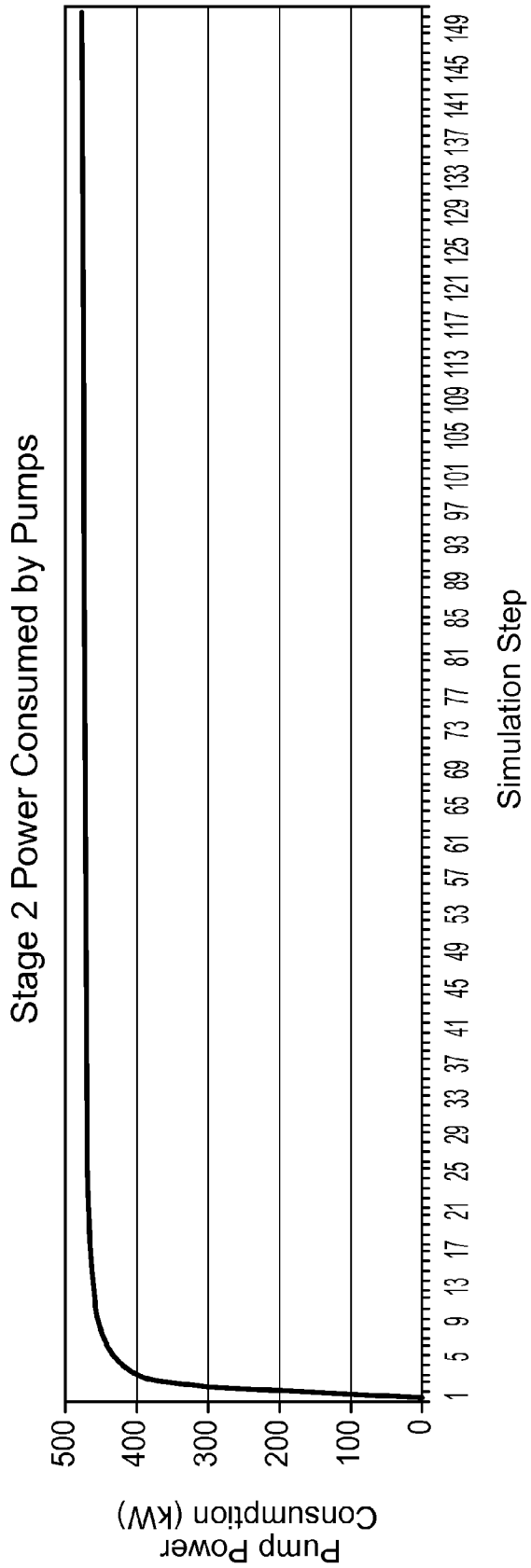

Stage 2 Power Consumed by Pumps
Pump Power Consumption (kW)
500
400
300
200
100
0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step

FIG. 44

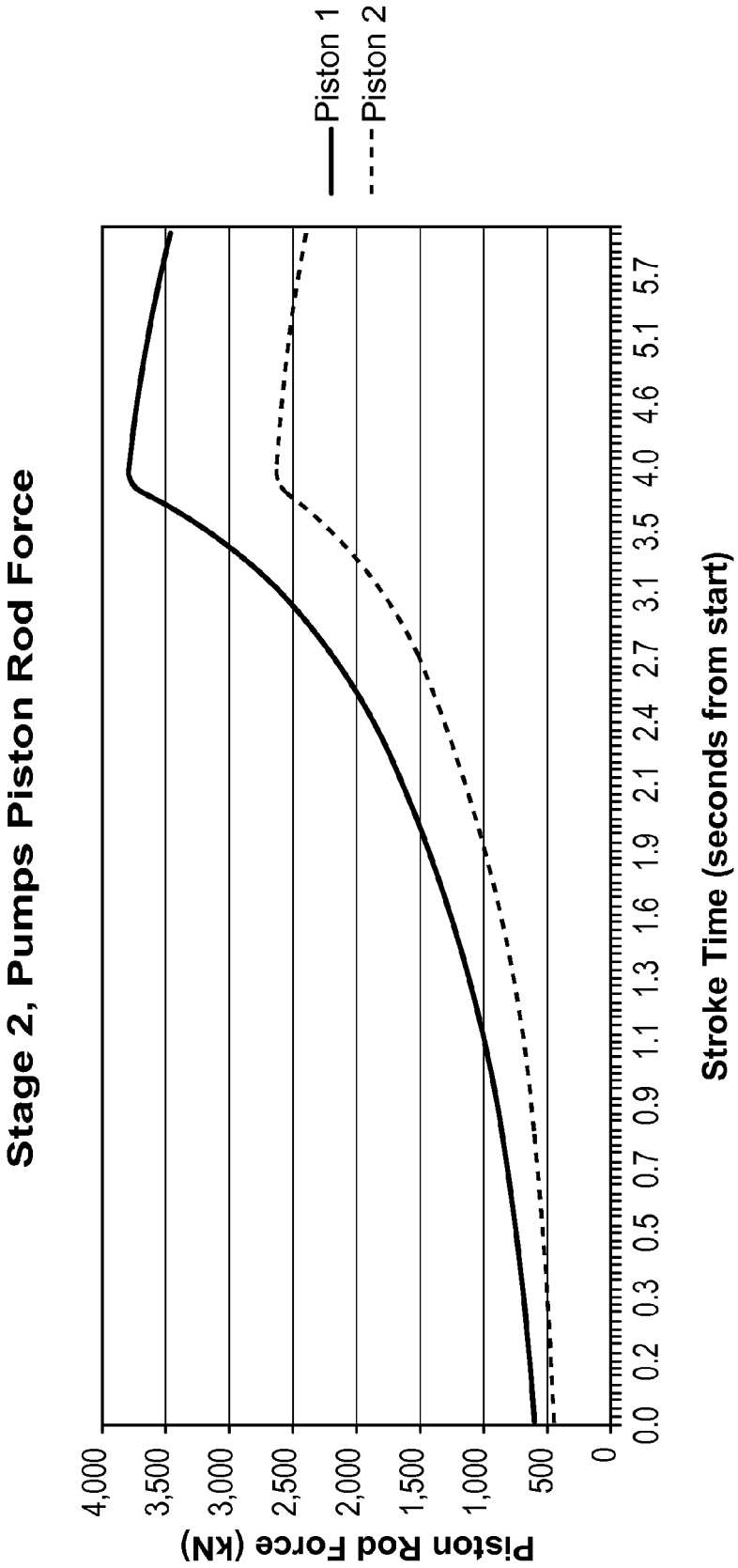

Stage 2, Pumps Piston Rod Force
Piston 1
Piston 2
Piston Rod Force (kN)
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0.0 0.2 0.3 0.5 0.7 0.9 1.1 1.3 1.6 1.9 2.1 2.4 2.7 3.1 3.5 4.0 4.6 5.1 5.7
Stroke Time (seconds from start)

FIG. 45

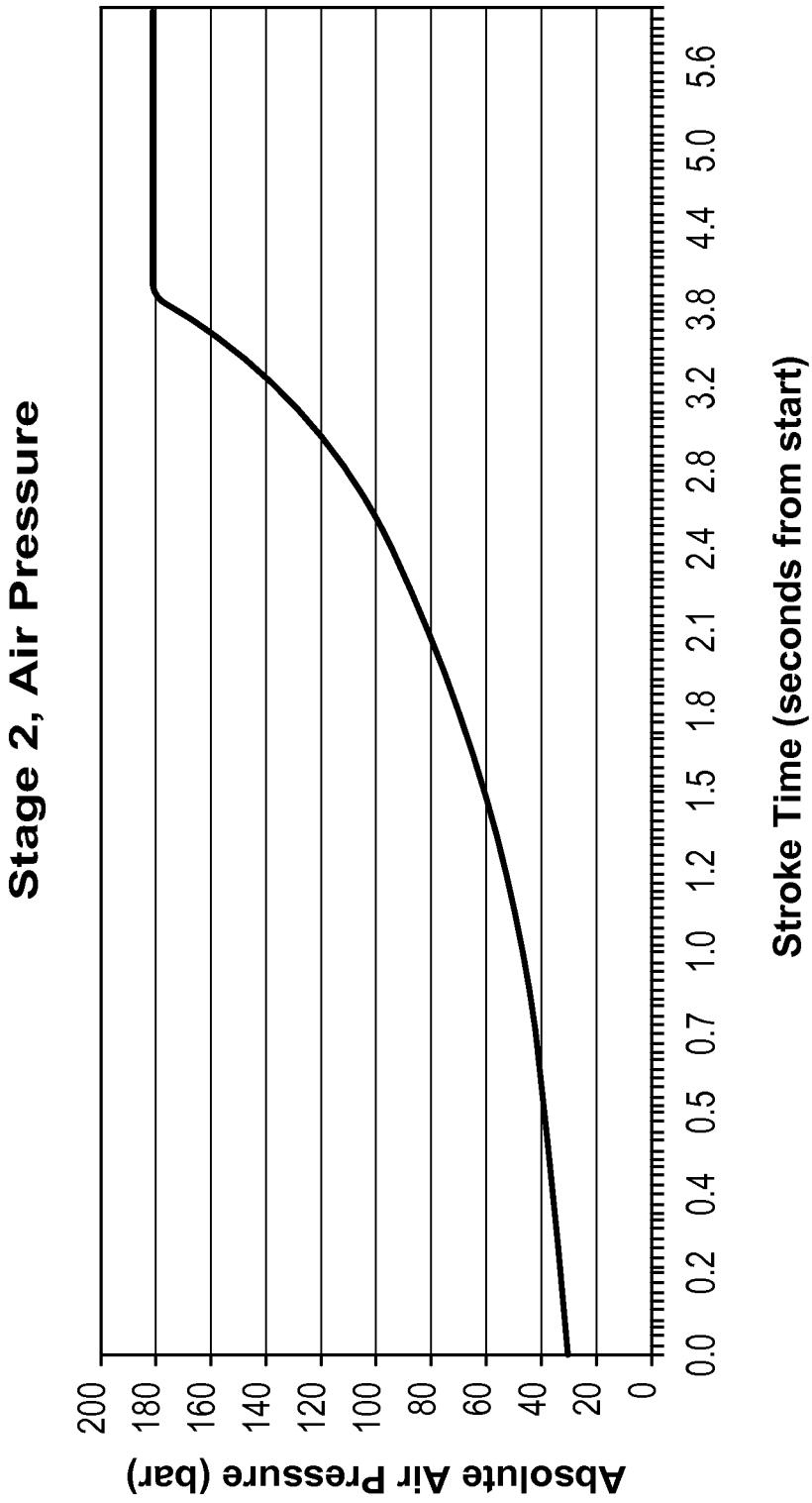

Stage 2, Air Pressure
Absolute Air Pressure (bar)
200
180
160
140
120
100
80
60
40
20
0
0.0
0.2
0.4
0.5
0.7
1.0
1.2
1.5
1.8
2.1
2.4
2.8
3.2
3.8
4.4
5.0
5.6
Stroke Time (seconds from start)

FIG. 46

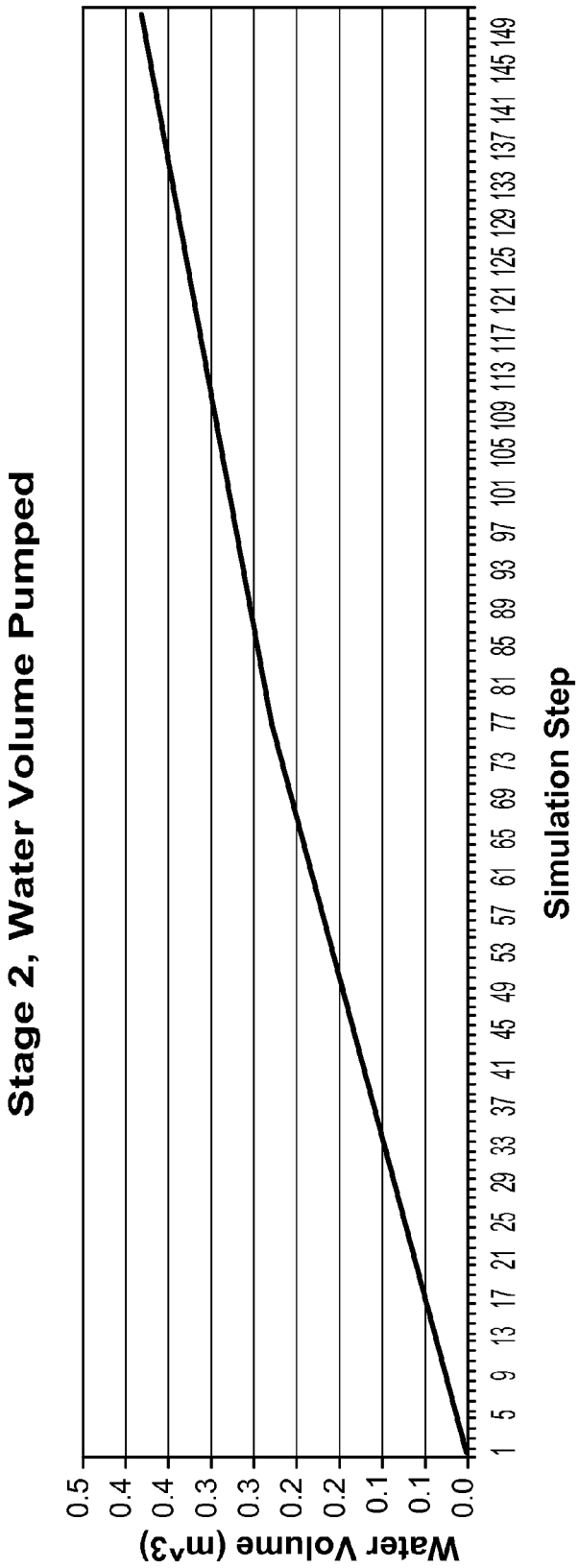

Stage 2, Water Volume Pumped
Water Volume (m^3)
0.5
0.4
0.4
0.3
0.3
0.2
0.2
0.1
0.1
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step

FIG. 47

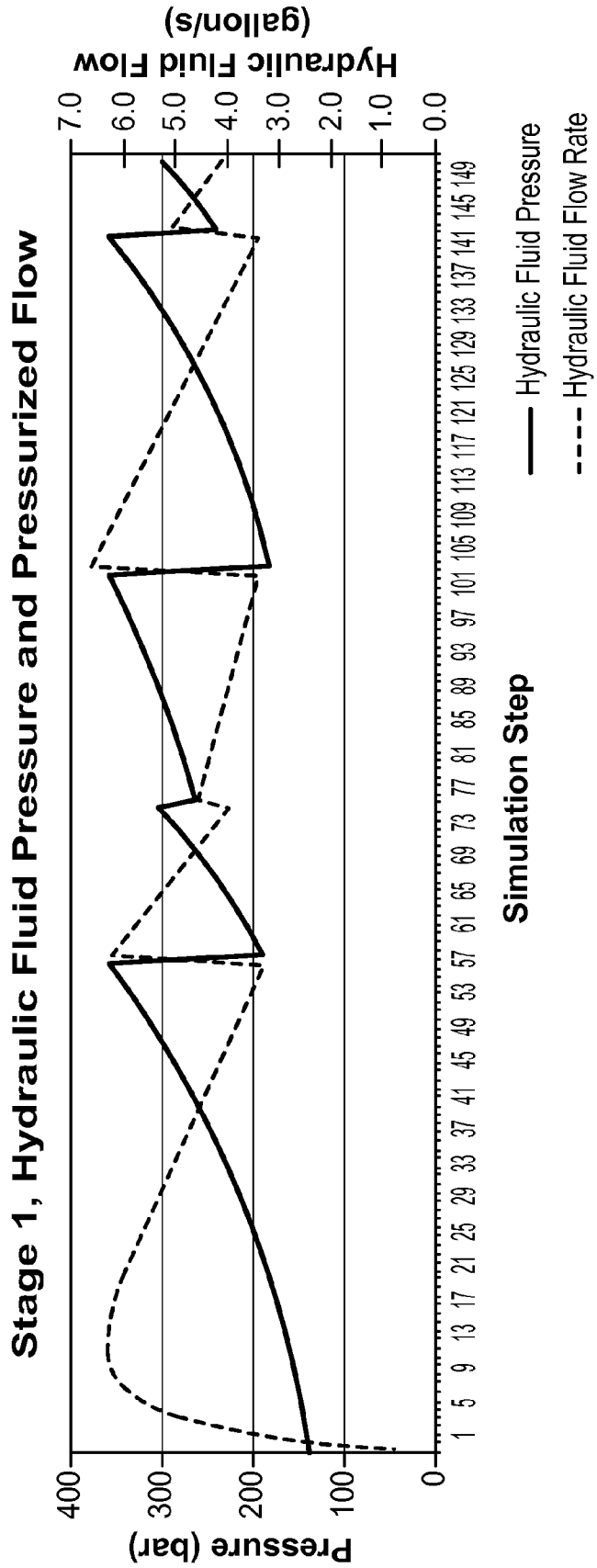

Stage 1, Hydraulic Fluid Pressure and Pressurized Flow
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate

FIG. 48

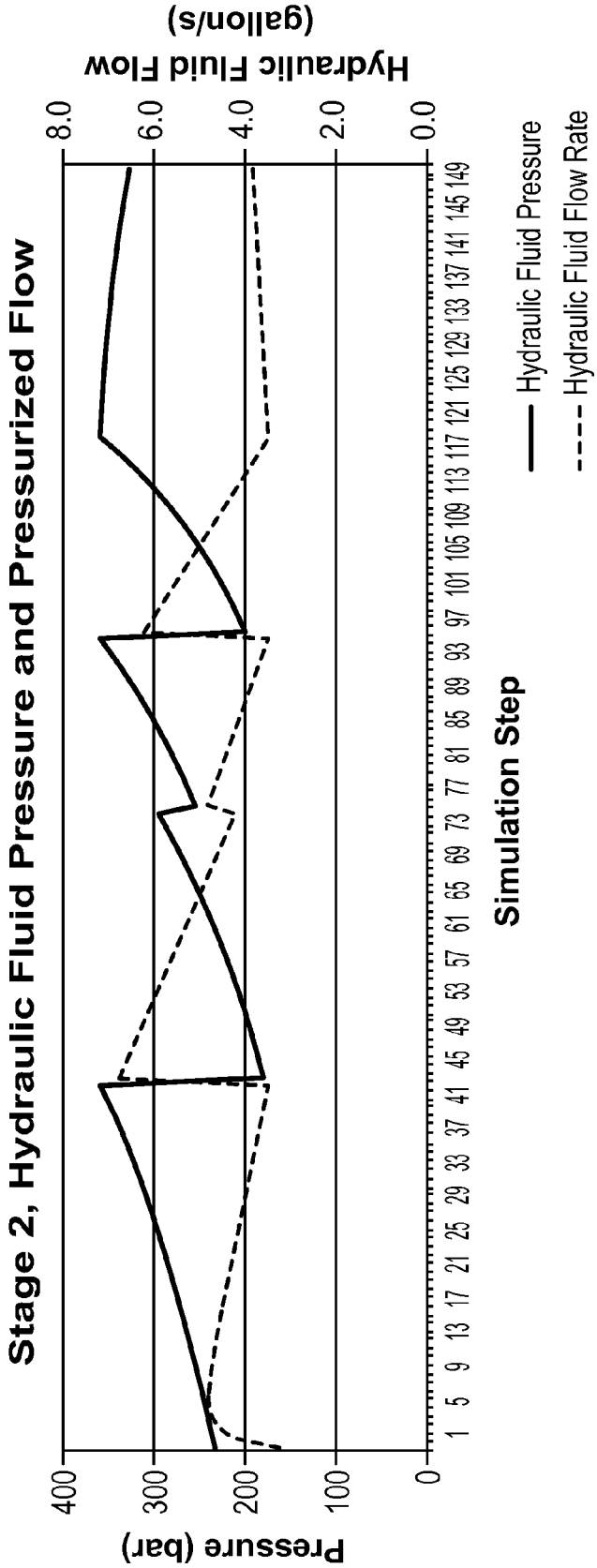

Stage 2, Hydraulic Fluid Pressure and Pressurized Flow
Pressure (bar)
400
300
200
100
0
Hydraulic Fluid Flow (gallon/s)
8.0
6.0
4.0
2.0
0.0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Simulation Step
Hydraulic Fluid Pressure
Hydraulic Fluid Flow Rate

FIG. 49

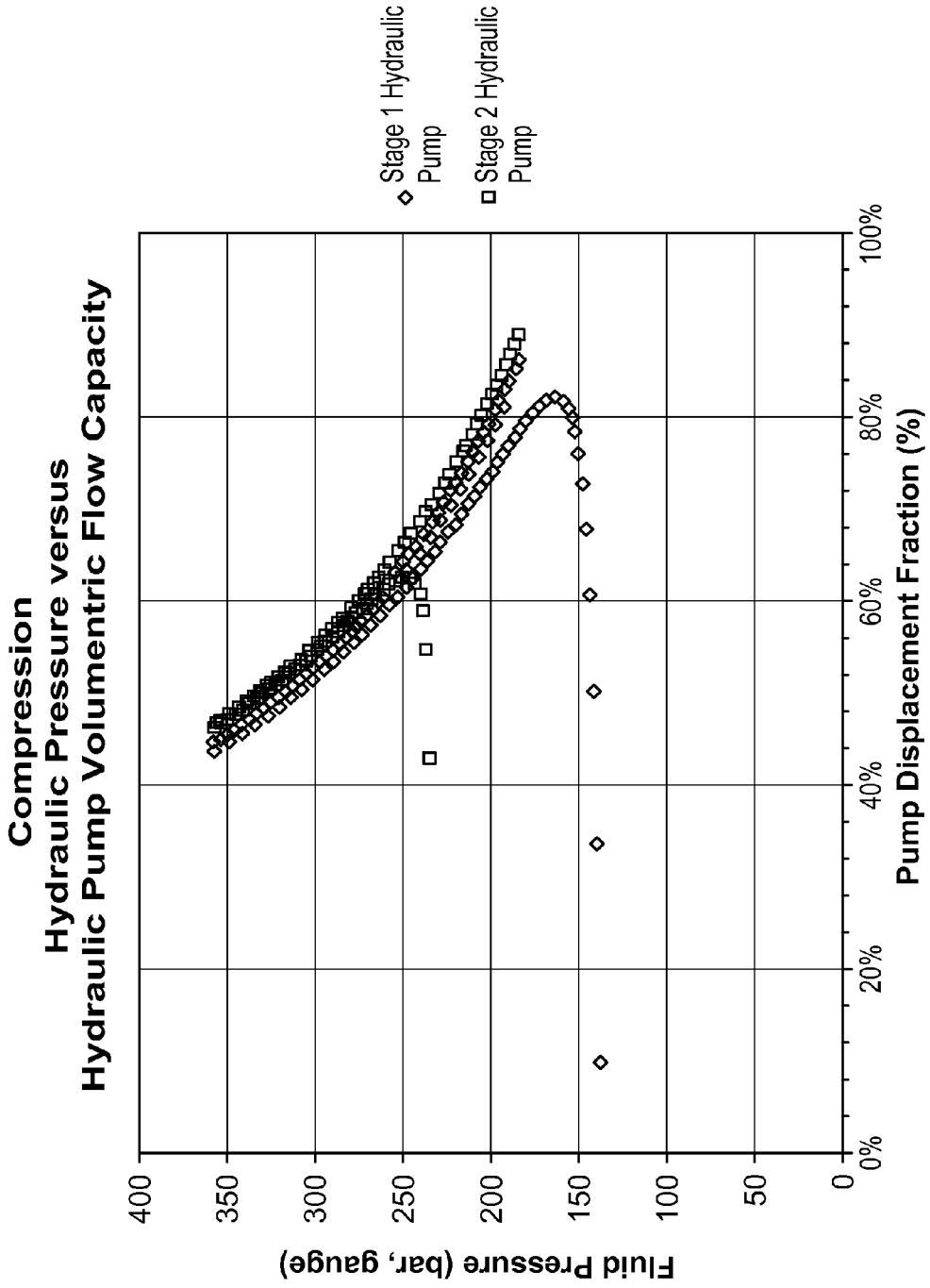

Compression
Hydraulic Pressure versus
Hydraulic Pump Volumentric Flow Capacity
Stage 1 Hydraulic Pump
Stage 2 Hydraulic Pump
Fluid Pressure (bar, gauge)
400
350
300
250
200
150
100
50
0
0%
20%
40%
60%
80%
100%
Pump Displacement Fraction (%)

FIG. 50

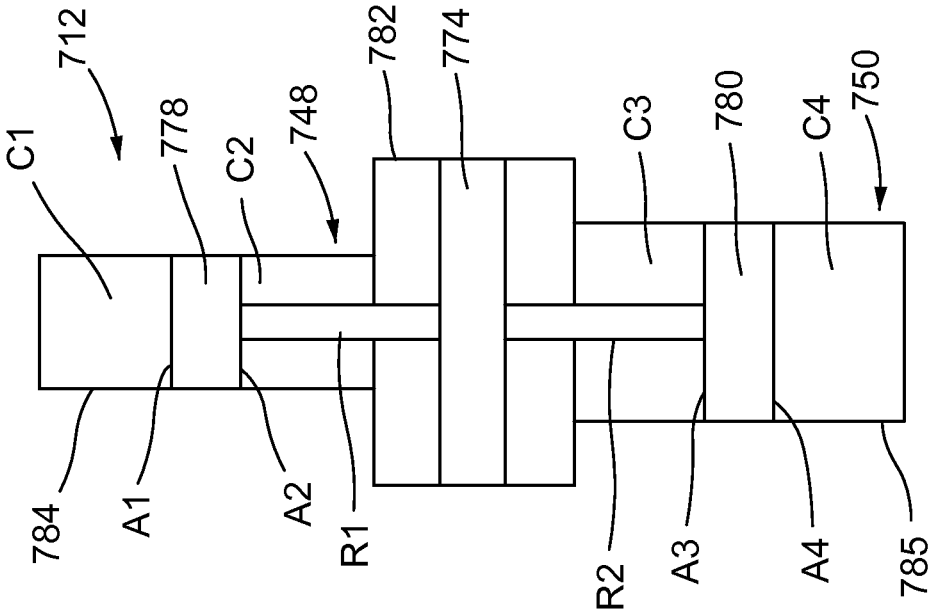


FIG. 51A

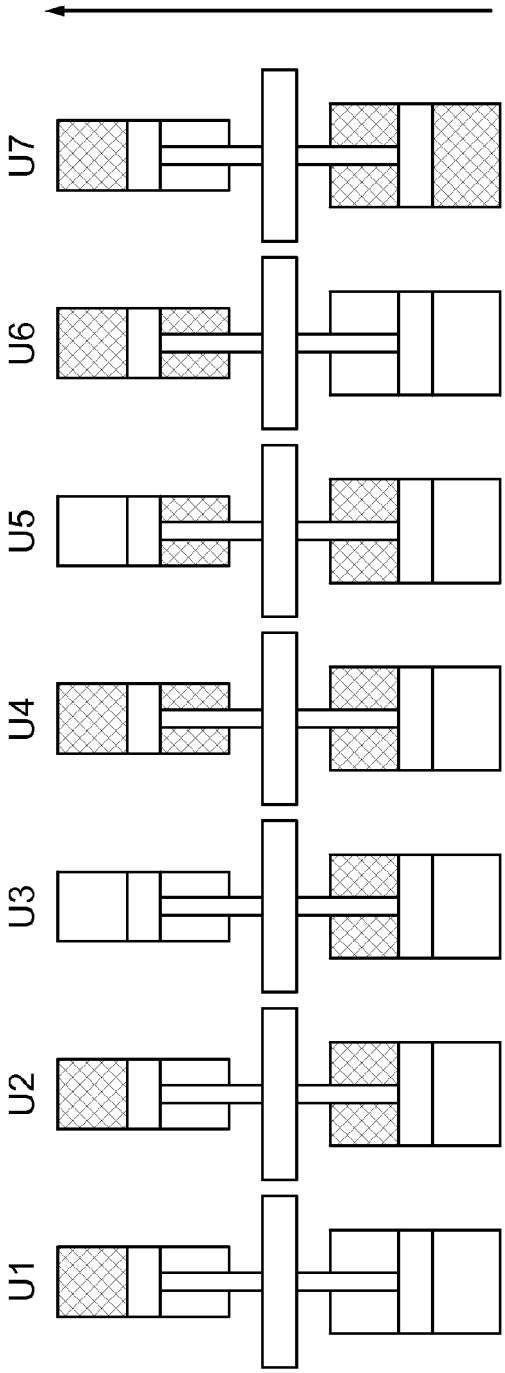


FIG. 51B

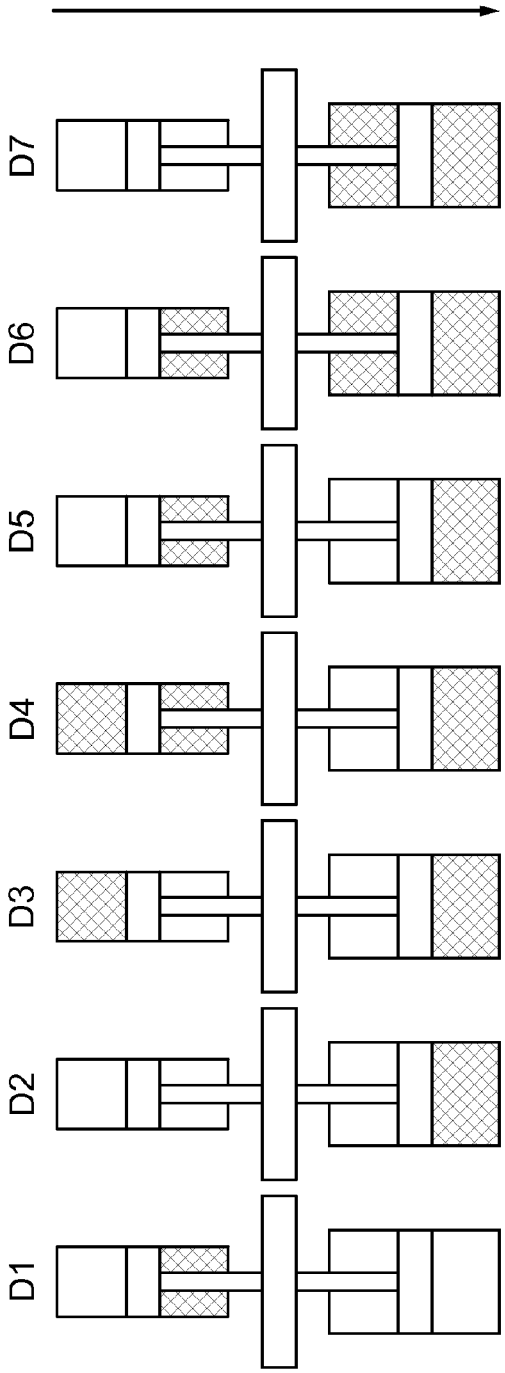


FIG. 51C

Chamber	Hydraulic Piston Area	DIR	D1	D2	D3	D4	D5	D6	D7	–	U1	U2	U3	U4	U5	U6	U7	U8
C1	A1	Down	P	P	N	N	P	P	P	N	N	N	P	N	P	N	N	P
C2	A2	Up	N	P	P	N	N	N	P	N	P	P	P	N	N	N	P	P
C3	A3	Down	P	P	P	P	P	N	N	N	P	N	N	N	N	P	N	P
C4	A4	Up	P	N	N	N	N	N	N	N	P	P	P	P	P	P	N	P
Net Surface Area	A1 < A3 A2 < A4 Rod 2 < Rod 3		A1 + A3 – A4	A1 – A2 + A3	A3 – A2	A3	A1 + A3	A1	A1 – A2	0	- A2 + A3 – A4	- A2 – A4	A1 – A2 - A4	- A4	A1 – A4	A3 – A4	- A2	A1 – A2 + A3 – A4
			D1	D2	D3	D4	D5	D6	D7		U1	U2	U3	U4	U5	U6	U7	U8
Identical cylinders	A1 = A4 A2 = A3 Rod 2 = Rod 3		A3	A1	0	A3	A1 + A3	A1	A1 – A2	0	- A4	- A2 – A4	- A2	- A4	0	A3 – A4	-A2	0

FIG. 51D

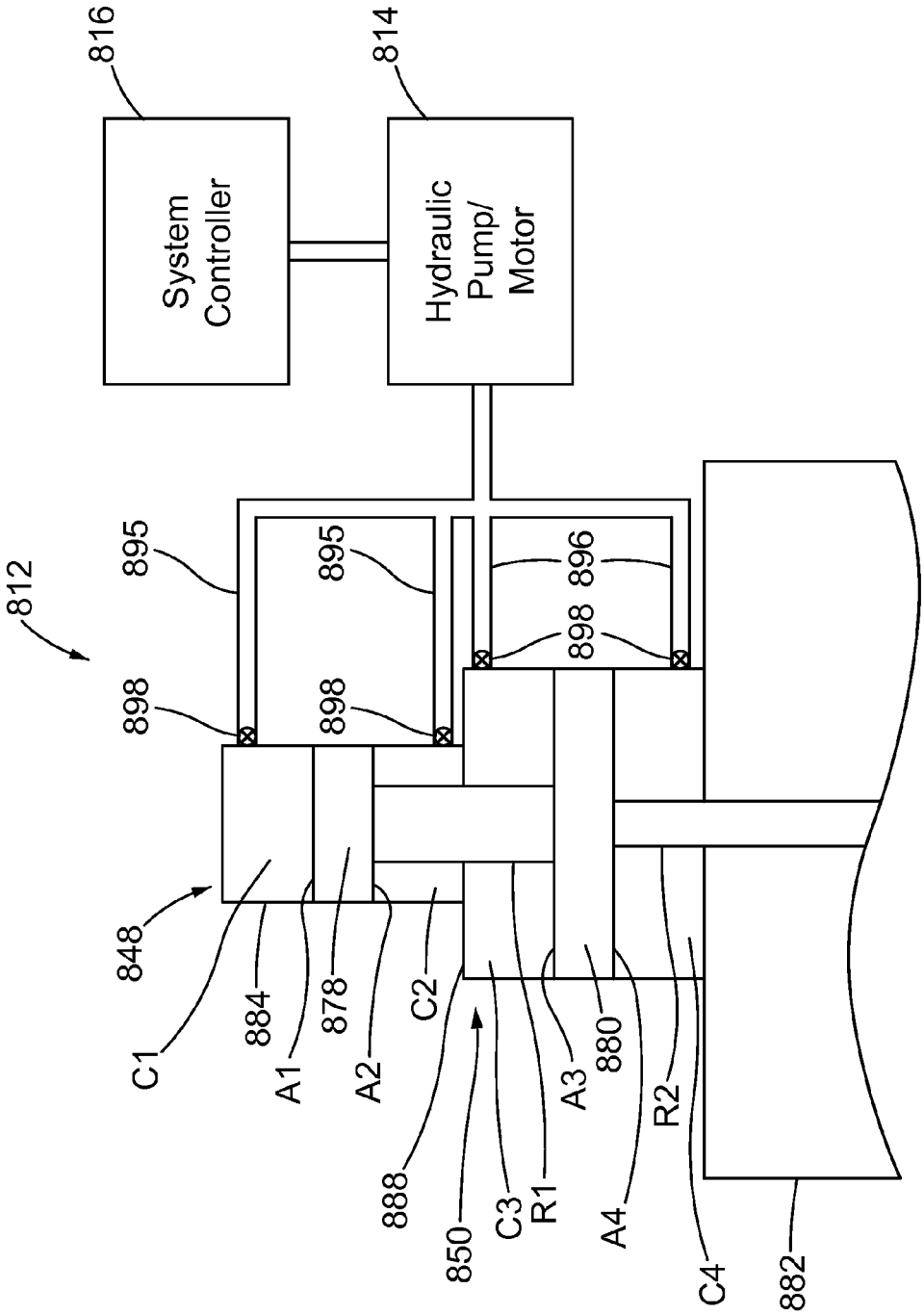

816
System Controller
814
Hydraulic Pump/ Motor
812
895
895
896
898
898
898
848
C1
884
A1
878
A2
C2
888
850
C3
R1
A3
880
A4
R2
C4
882

FIG. 52A

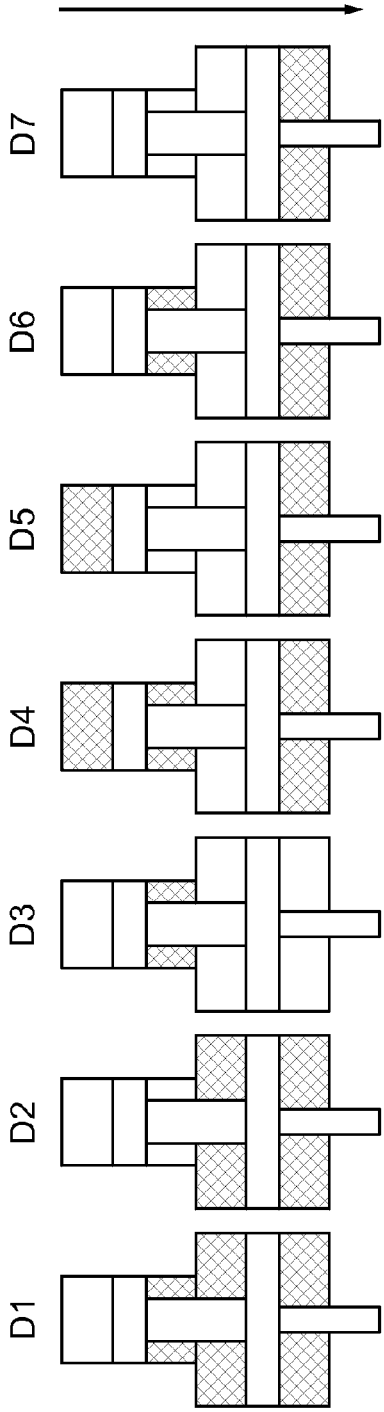


FIG. 52B

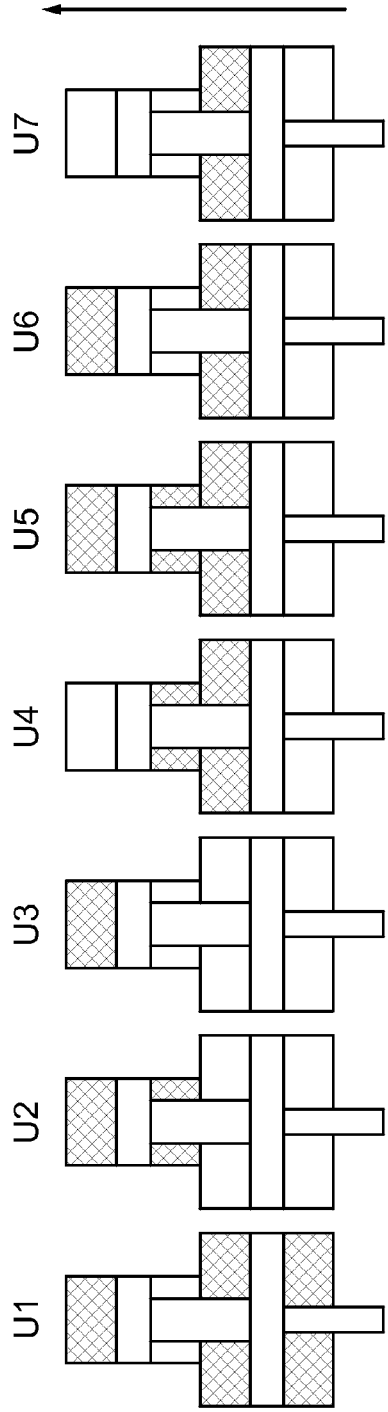


FIG. 52C

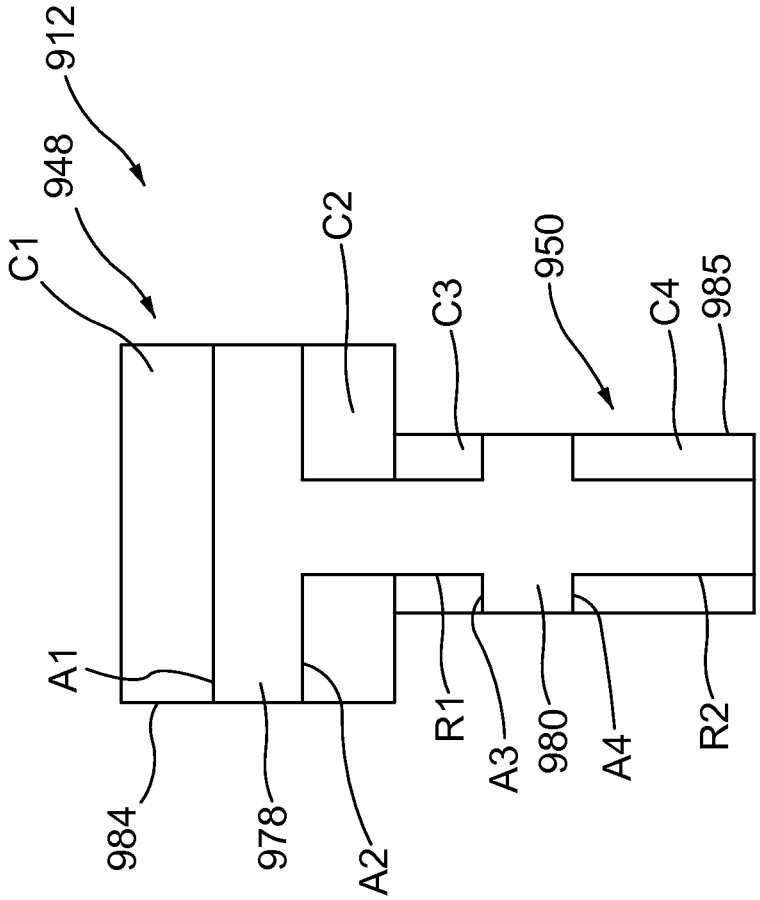


FIG. 53

FIG. 54A

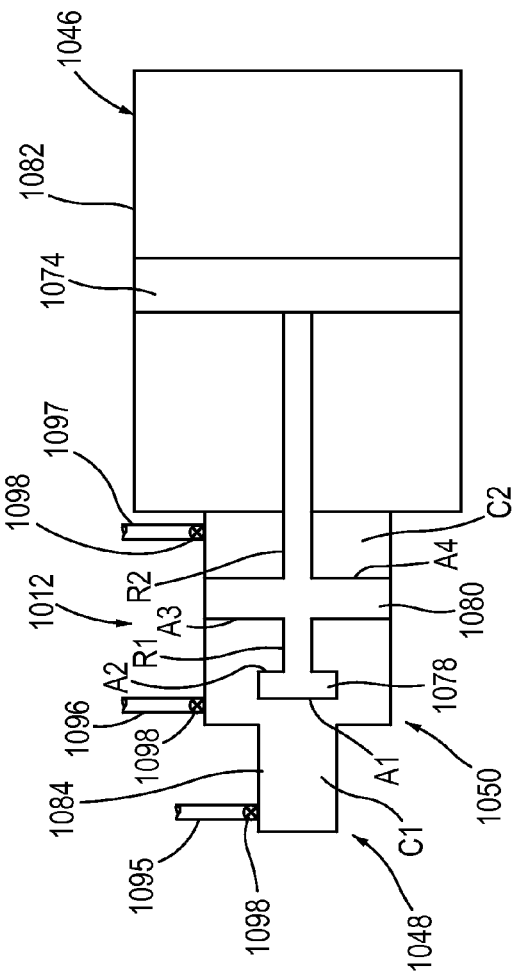
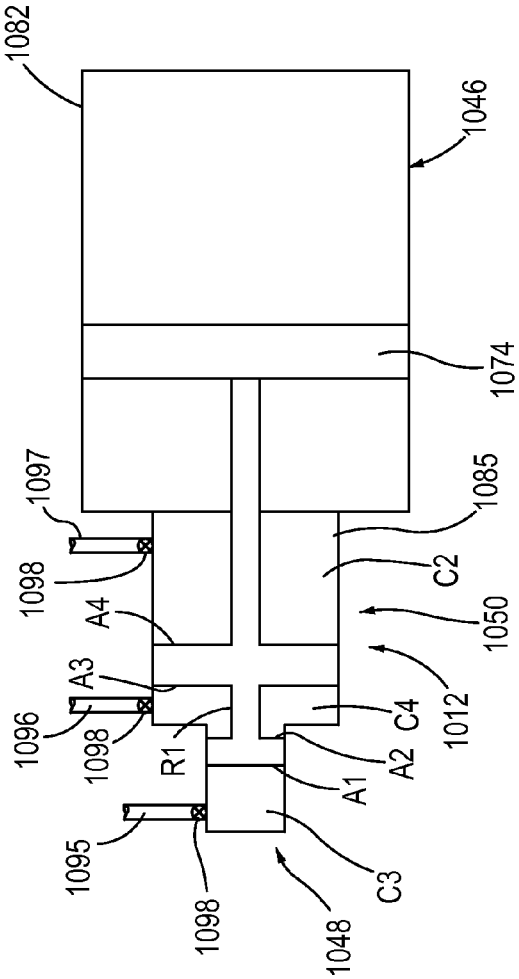


FIG. 54B



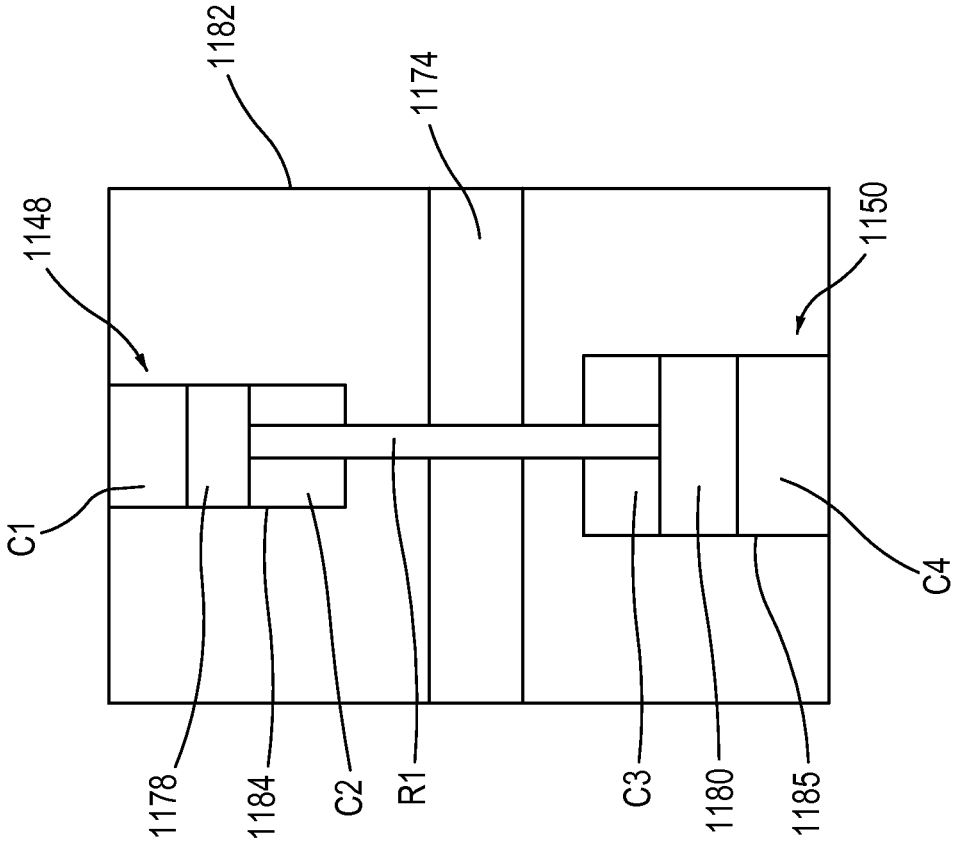


FIG. 55

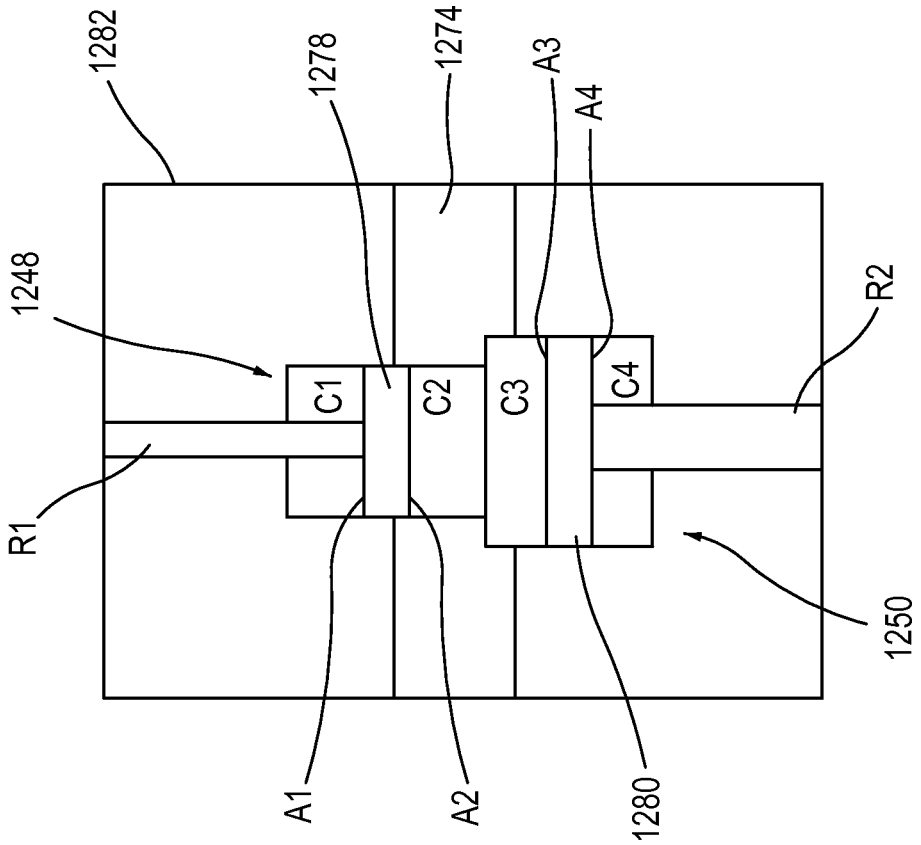


FIG. 56

SYSTEM AND METHODS FOR OPTIMIZING EFFICIENCY OF A HYDRAULICALLY ACTUATED SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 12/977,724, filed Dec. 23, 2010, entitled "System and Methods for Optimizing Efficiency of a Hydraulically Actuated System," which claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/290,107, filed Dec. 24, 2009, entitled "System and Methods for Optimizing Efficiency of a Hydraulically Actuated System," the disclosures of which are hereby incorporated by reference in their entirety.

BACKGROUND

The invention relates generally to systems and methods of optimizing the energy efficiency of hydraulic actuation systems, for use in, for example, storing energy using a system and methods for optimizing the efficiency of a compressed air energy storage system.

Traditionally, electric power plants have been sized to accommodate peak power demand. Moreover, electric power plant sizing must take into account their maximum power output, minimum power output, and a middle power output range within which they most efficiently convert fuel into electricity. Electric power plants are also constrained in terms of how quickly they can start-up and shut-down, and it is commonly infeasible to completely shut-down a power plant. The combination of power output constraints, and start-up and shut-down constraints, restricts a power plant's ability to optimally meet a fluctuating power demand. These restrictions may lead to increased green house gas emissions, increased overall fuel consumption, and/or to potentially higher operating costs, among other drawbacks. Augmenting a power plant with an energy storage system may create an ability to store power for later use, which may allow a power plant to fulfill fluctuating consumer demand in a fashion that minimizes these drawbacks.

An energy storage system may improve overall operating costs, reliability, and/or emissions profiles for electric power plants. Existing energy storage technologies, however, have drawbacks. By way of example, batteries, flywheels, capacitors and fuel cells may provide fast response times and may be helpful to compensate for temporary blackouts, but have limited energy storage capabilities and may be costly to implement. Installations of other larger capacity systems, such as pumped hydro systems, require particular geological formations that might not be available at all locations.

Intermittent electric power production sites, such as some wind farms, may have capacities that exceed transmission capabilities. Absent suitable energy storage systems, such intermittent power production sites may not be capable of operating at full capacity. The applicants have appreciated that intermittent production sites may benefit from a storage system that may be sized to store energy, when the production site is capable of producing energy at rates higher than may be transmitted. The energy that is stored may be released through the transmission lines when power produced by the intermittent site is lower than transmission line capacity.

Electric power consumption sites, such as buildings, towns, cities, commercial facilities, military facilities, may have consumption that periodically exceeds electricity transmission capabilities. Absent suitable energy storage systems, such power consumers may not be capable of operating at preferred levels. The applicants have appreciated that transmission constrained consumption sites may benefit from a storage system that may be sized to store energy, when the consumption site is consuming energy at rates lower than may be transmitted, and that the transmitted energy that is not immediately consumed may be stored. The energy that is stored may be released to the consumers when power consumption of the consumers is higher than the transmission line capacity.

Compressed air energy storage systems (CAES) are another known type of system in limited use for storing energy in the form of compressed air. CAES systems may be used to store energy, in the form of compressed air, when electricity demand is low, typically during the night, and then to release the energy when demand is high, typically during the day. Such systems include a compressor that operates, often at a constant speed, to compress air for storage. Turbines, separate from the compressor, are typically used to expand compressed air to produce electricity. Turbines, however, often require the compressed air to be provided at a relatively constant pressure, such as around 35 atmospheres. Additionally or alternatively, air at pressures higher than 35 atmospheres may need to be throttled prior to expansion in the turbine, causing losses that reduce the efficiency of the system, and/or reduce the energy density that a storage structure may accommodate. Additionally, to increase electrical energy produced per unit of air expanded through the turbine, compressed air in such systems is often pre-heated to elevated temperatures (e.g., 1000 C) prior to expansion by burning fossil fuels that both increases the cost of energy from the system and produces emissions associated with the storage of energy.

Known CAES-type systems for storing energy as compressed air have a multi-stage compressor that may include intercoolers that cool air between stages of compression and/or after-coolers that cool air after compression. In such a system, however, the air may still achieve substantial temperatures during each stage of compression, prior to being cooled, which will introduce inefficiencies in the system. Thus, there is a need to provide for CAES type systems that have improved efficiencies.

A CAES system may be implemented using a hydraulic drive system comprised of hydraulic components including components such as hydraulic pumps. Therefore, there is also a need for a system and methods to obtain a high efficiency output of a compressed air energy storage system, or other systems used to compress and/or expand gas, including controls and operating modes that allow for adjusting or varying the pressures and/or flow rates of hydraulic fluid within hydraulic pumps used in operation of such a system.

SUMMARY OF THE INVENTION

Systems and methods for efficiently operating a hydraulically actuated device/system are described herein. For example, systems and methods for efficiently operating a gas compression and expansion energy storage system are disclosed herein. Systems and methods are provided for controlling and operating the hydraulic pumps/motors used within a hydraulically actuated device/system, such as, for example, a gas compression and/or expansion energy system, within a maximum efficiency range of the pumps throughout an entire cycle of the system. In such a system, a variety of different operating regimes can be used depending on the desired output gas pressure and the desired stored pressure of the compressed gas. Hydraulic cylinders used to drive working pis-

tons within the system can be selectively actuated and/or can be actuated to achieve varying force outputs to incrementally increase the gas pressure, within the system for a given cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of an air compression and expansion energy system according to an embodiment.

FIG. **2**A is a schematic illustration of an air compression and expansion energy system showing the flow of energy during a compression cycle, according to one embodiment

FIG. **2**B is a schematic illustration of an air compression and expansion energy system showing the flow of energy during an expansion cycle, according to one embodiment

FIG. **3** shows a single stage of one embodiment of an air compression and expansion system.

FIG. **4** illustrates an embodiment of a divider that can be used in a pressure vessel.

FIG. **5**A is a schematic illustration of a portion of another embodiment of an air compression and expansion system.

FIG. **5**B is a schematic illustration of a portion of the air compression and expansion system of FIG. **5**A illustrating a system controller and hydraulic pump.

FIGS. **6**A and **6**B are each a schematic illustration of a portion of an actuator of the air compression and expansion system of FIG. **5**.

FIG. **6**C is a side view of a portion of an actuator of the system of FIG. **5**.

FIG. **6**D is a cross sectional view taken along line **6**D-**6**D in FIG. **6**C.

FIG. **6**E is an end view taken along line **6**E-**6**E in FIG. **6**C.

FIG. **6**F is a cross sectional view taken along line **6**F-**6**F in FIG. **6**C.

FIGS. **7**-**14** illustrate a process of compressing air with the system of FIG. **5** according to an embodiment.

FIGS. **15**-**22** illustrate a process of expanding air with the system of FIG. **5**, according to an embodiment.

FIGS. **23**-**50** are each an example graph illustrating various parameters associated with the operation and output of a compression and expansion system according to various embodiments.

FIG. **51**A is a schematic illustration of an actuator according to an embodiment.

FIG. **51**B and FIG. **51**C each include multiple schematic illustrations of the actuator of FIG. **51**A showing different gears of the actuator.

FIG. **51**D is a table illustrating various parameters related to implementing multiple different gears shown in FIG. **51**B and FIG. **51**C.

FIG. **52**A is a schematic illustration of an actuator according to another embodiment.

FIG. **52**B and FIG. **52**C each include multiple schematic illustrations of the actuator of FIG. **52**A showing different gears of the actuator.

FIG. **53** is a schematic illustration of an actuator according to another embodiment.

FIG. **54**A is a schematic illustration of an actuator according to another embodiment, shown in a first configuration.

FIG. **54**B is a schematic illustration of the actuator of FIG. **54**A, shown in a second configuration.

FIG. **55** is a schematic illustration of an actuator according to another embodiment.

FIG. **56** is a schematic illustration of an actuator according to another embodiment.

DETAILED DESCRIPTION

Systems and methods for efficiently operating a gas compression and/or expansion system are disclosed herein. The gas compression and/or expansion systems can use one or more hydraulic pumps/motors to move (or be moved by) gas and liquid within the system, and systems and methods are described herein to operate the hydraulic pump/motor in its most efficient regime, continuously or substantially continuously, during an operating cycle or stroke of the system. Hydraulic pumps can have efficient operating ranges that can vary as a function of, for example, flow rate and pressure, among other parameters. Systems and methods of operating the hydraulic pumps/motors are provided to allow them to function at an optimal efficiency throughout the stroke or cycle of the gas compression and/or expansion system.

As described herein, in some embodiments, hydraulic pumps/motors can be used to drive (or be driven by) a working piston within a gas compression and/or expansion system, in which a working piston can act on (or be acted on) gas contained in a working chamber to compress or expand the gas, directly, or indirectly through a liquid disposed between the working piston and the gas in the working chamber. The hydraulic loads applied to the working piston(s) can be varied during a given cycle of the system. For example, by applying hydraulic fluid pressure to different hydraulic pistons, and/or different surfaces of the piston(s) within the hydraulic pump(s)/motor(s), the ratio of the net working surface area of the hydraulic actuator to the working surface area of the working piston acting on the gas in the working chamber can be varied, and therefore the ratio of the hydraulic fluid pressure to the gas pressure in the working chamber can be varied during a given cycle or stroke of the system. In addition, the number of working pistons/working chambers and hydraulic cylinders can be varied as well as the number of piston area ratio changes within a given cycle. As used herein the term "piston" is not limited to pistons of circular cross-section, but can include pistons with a cross-section of a triangular, rectangular, or other multi-sided shape.

A gas compression and/or expansion system as described herein can include one or multiple stages of compression and/or expansion. For example, a system can include a single stage compression/expansion device, two stages, three stages, etc. As described herein, a system can also include "gear shifts" or "gear changes" within a given stage as will be described in detail below with reference to specific embodiments. As used herein, the terms "gear change" or "gear shift" are used to described a change in the ratio of the pressure of the hydraulic fluid in the active hydraulic actuator chambers to the pressure of the gas in the working chamber actuated by (or actuating) the hydraulic actuator, which is essentially the ratio of the pressurized surface area of the working piston(s) to the net area of the pressurized surface area(s) of the hydraulic piston(s) actuating the working piston(s). As used herein the term "gear" can refer to a state in which a hydraulic actuator has a particular piston area ratio (e.g., the ratio of the net working surface area of the hydraulic actuator to the working surface area of the working piston acting on, or being acted on by, the gas in a working chamber) at a given time period.

In some embodiments, a hydraulic actuator as described herein can be used to drive, or be driven by, a working piston within, for example, a water pump/motor, to move water (or other liquid) in and out of the working chamber of a pressure vessel used to compress and/or expand a gas, such as air, contained in the working chamber. As described herein, an actuator can also include "gear shifts" or "gear changes" (described above) during a cycle or stroke of the actuator. In some embodiments, an actuator as described herein can be used to drive, or be driven by, a working piston disposed within a compression and/or expansion device. For example,

in some such embodiments, the working piston can be driven to compress one or more fluids within a working chamber. As used herein, "fluid" can mean a liquid, gas, vapor, suspension, aerosol, or any combination thereof. Although particular embodiments of an actuator are described herein to drive, or be driven by, a water pump/motor and/or a compression and/or expansion device, it should be understood that the various embodiments and configurations of an actuator can be used to drive, or be driven by, a working piston within a water pump, a compression and expansion device, a compression device, an expansion device, any other device in which a working piston is used to move a fluid, and/or any device to which motive force can be applied or from which motive force can be received.

In some embodiments, the devices and systems described herein can be configured for use only as a compressor. For example, in some embodiments, a compressor device described herein can be used as a compressor in a natural gas pipeline, a natural gas storage compressor, or any other industrial application that requires compression of a gas. In another example, a compressor device described herein can be used for compressing carbon dioxide. For example, carbon dioxide can be compressed in a process for use in enhanced oil recovery. In another example, a compressor device described herein can be used for compressing air. For example, compressed air can be used in numerous applications which may include cleaning applications, motive applications, ventilation applications, air separation applications, cooling applications, amongst others.

In some embodiments, the devices and systems described herein can be configured for use only as an expansion device. For example, an expansion device as described herein can be used to generate electricity. In some embodiments, an expansion device as described herein can be used in a natural gas transmission and distribution system. For example, at the intersection of a high pressure (e.g., 500 psi) transmission system and a low pressure (e.g., 50 psi) distribution system, energy can be released where the pressure is stepped down from the high pressure to a low pressure. An expansion device as described herein can use the pressure drop to generate electricity.

In some embodiments, a compression and/or expansion device as described herein can be used in an air separation unit. In one example application, in an air separator, a compression and/or expansion device can be used in a process to liquefy a gas. For example, air can be compressed until it liquefies and the various constituents of the air can be separated based on their differing boiling points. In another example application, a compression and/or expansion device can be used in an air separator co-located with in a steel mill where oxygen separated from the other components of air is added to a blast furnace to increase the burn temperature.

A compression and/or expansion system can have a variety of different configurations and can include one or more actuators that are use to compress/expand air within a compression/expansion device. In some embodiments, an actuator can include one or more pump/motor systems, such as for example, one or more hydraulic pumps/motors that can be use to move, or be moved by, one or more fluids within the system between various water pumps/motors and pressure vessels. U.S. provisional patent application No. 61/216,942, filed May 22, 2009, and U.S. patent application Ser. Nos. 12/785,086, 12/785,093 and 12/785,100, each filed May 21, 2010 and entitled "Compressor and/or Expander Device (collectively referred to herein as the "the Compressor and/or Expander Device applications"), the disclosures of which are hereby incorporated herein by reference, in their entireties, describe various energy compression and/or expansion systems in which the systems and methods described herein can be employed.

As background, FIG. **1** is a schematic illustration of an embodiment of an energy system **100** in which a compressor/expander device may be used to both store energy and release energy that has previously been stored. As shown in FIG. **1**, a wind farm **102** including a plurality of wind turbines **104** may be used to harvest and convert wind energy to electric energy for delivery to a motor/generator **110**. It is to be appreciated that the system **100** may be used with electric sources other than wind farms, such as, for example, with the electric power grid, or solar power sources. The motor/generator **110** converts the input electrical power from the wind turbines or other sources into mechanical power. That mechanical power can then be used to drive a hydraulic pump/motor **111**. In turn, the hydraulic pump/motor converts the input mechanical power into hydraulic power, which can be used to drive a hydraulic actuator **112** connected to a compressor/expander device **120**.

Energy can be stored within the system **100** in the form of compressed gas, which can be expanded at a later time period to access the energy previously stored. To store energy generated by the wind farm **102**, the hydraulic actuator **112** can change the volume of a working chamber (e.g. by moving a piston in a cylinder) and/or to cause liquid to be introduced into the working chamber to reduce the volume available within the working chamber for gas. The reduction in volume compresses the gas. During this process, heat can be removed from the gas. During compression, the gas is delivered to a downstream stage of the compressor/expander device **120** and eventually, at an elevated pressure, to a compressed gas storage structure **122** (also referred to herein as a "cavern"). At a subsequent time, for example, when there is a relatively high demand for power on the power grid, or when energy prices are high, compressed gas may be communicated from the storage structure **122** and expanded through the compressor/expander device **120**. Expansion of the compressed gas drives the hydraulic actuator **112** that, in turn, drives, by hydraulic power, the hydraulic pump/motor **111** to produce mechanical power, which in turn drives motor/generator **110** to produce electric power for delivery to the power grid **124**. Heat at a relatively low temperature (e.g., between for example, about 10° C. and about 90° C.) may be added to the gas during expansion to increase the energy generated per unit mass of air during the expansion process. Heat at relatively high temperatures (e.g. greater than about 90° C.) may be added during expansion to increase the energy generated per unit mass of air during the expansion process.

FIG. **2**A is a schematic illustration of energy flow through a multi-stage system **200** similar to the system **100** of FIG. **1**, at one example operating condition. A gas, in this example air, is being compressed for storage. As described above, electric power from, for example, a wind farm, is used to drive a motor/generator **210** to produce mechanical power, which in turn drives hydraulic pump/motor **211** to produce hydraulic power, which in turn drives an actuator **212**. Actuator **212** can reduce the volume of a working chamber available to contain air to be reduced, which compresses the air.

As shown in FIG. **2**A, a multi-stage compressor/expander device **220** can receive ambient air at a first stage of the compressor/expander device **220**. In some embodiments, ambient air can optionally be processed in a pre-compressor **215** prior to being provided to the first stage of the compressor/expander device **220**. Heat energy can be removed during compression via a liquid that is present in the working chamber(s) of a multi-stage compressor/expander device **220** to

maintain the air that is being compressed at a relatively constant temperature. The heat energy can be transferred from the liquid and the compressor/expander device **220** to, for example, a heat sink via, for example a heat exchanger. The air may achieve pressures of about, for example, 150 psi, 1,000 psi, and 3,000 psi at each of first, second, and third stages, respectively, before being delivered to a storage structure **222** at a pressure of about 3,000 psi, according to one embodiment. The temperature of the air, after being provided to the compressor/expander device **220**, and initially compressed and cooled, remains relatively constant, such as, for example, at about 5° C., 10° C., 20° C., 30° C. or other temperatures that may be desirable, until discharged to the storage structure **222**. Air stored in the storage structure **220** may be heated (or cooled) naturally through conductive and convective heat transfer if the storage structure **222** is naturally at a higher (or lower) temperature. For example, in some cases, the storage structure may be an underground structure, such as a salt cavern constructed in a salt dome. It is to be appreciated that FIG. **2**A illustrates one operating condition for one embodiment of a system, and that other operating conditions exist and other system embodiments are also contemplated.

FIG. **2**B is a schematic representation of energy flow through the system **200** of FIG. **2**A at one operating condition, as air is communicated from storage for the production of energy. In one example operating condition, air in the storage structure **222** can be at about 3000 psi, and can be expanded through the third, second, and first stages of the compressor/expander device to pressures of, for example, about 1000 psi, 150 psi, and 0 psi, respectively. Heat may be added to the air before and/or during expansion at each of the third, second, and first stages, respectively, to hold air temperatures at a substantially constant temperature, such as at about 35° C. or other temperatures, during the entire expansion process. It is to be appreciated, that the overall temperature change of air during expansion may be limited by a relatively large amount of air that expands in a relatively small volume of a pressure vessel and that is in contact with substantial heat transfer surfaces. It is to be appreciated, that it may be desirable to add heat to the air such that air temperature increases substantially, such as temperatures higher than 35° C. The compressor/expander device **220** produces mechanical power that is converted by hydraulic actuator **212** into hydraulic power, which is applied to hydraulic pump/motor **211**, which in turn converts the hydraulic power to mechanical power. The mechanical power is applied to motor/generator **210**, which converts the mechanical power to electric power. It is to be understood that actuators other than hydraulic actuators can alternatively be used. As another source of producing electric power, as the expanded air exits the first stage of the compressor/expander device **220**, the air can optionally be provided to an air turbine **217**, which can convert the air to mechanical power. The mechanical power can be applied to a motor/generator **219**, which converts the mechanical power to electric power.

FIG. **3** illustrates a portion of a compressed air storage system **300** that includes a compressor/expander device **320** and an actuator **312**. The compressor/expander device **320** illustrates a single stage of a compressed air storage system. The compressor/expander device **320** includes a first pressure vessel **324** and a second pressure vessel **326**. The first and second pressure vessels **324**, **326** are each coupled fluidly to the actuator **312** by a conduit or housing **328** and **330**, respectively. The actuator **312** can include a water pump that includes a hydraulically driven piston **332**. The piston **332** is disposed within a housing or reservoir **340** and can be driven with one or more hydraulic pumps (not shown in FIG. **3**) to move toward and away from the conduit **328** of first pressure vessel **324** to alternately reduce and then increase the internal air volume of the first pressure vessel **324** (with an equivalent, but opposite increase and reduction of air volume in the second pressure vessel **326**). Each of the first and second pressure vessels **324**, **326** are at least partially filled with a liquid, such as water, that is moved by the actuator **312** to alternately compress and drive air from the volume of each of the first and second pressure vessels **324**, **326**, when operated in a compression mode, or to be moved by compressed air received in either of the first and second pressure vessels **324**, **326** when operated in an expansion mode.

Each pressure vessel **324**, **326** can be considered to define a working chamber for compressing and/or expanding a gas. The working chamber has a volume that is defined by the volume of the pressure vessel. The working chamber has a portion of this volume that can contain gas and a portion that contains liquid—the portion of the volume that contains gas is equal to the total volume of the working chamber less the volume of the portion containing liquid. Operation of the water pump to urge liquid from the pump cylinder into the pressure vessel reduces the volume of the portion of the working chamber that can contain gas, thus compressing the gas contained in that portion (e.g. during a compression cycle). Similarly, operation of the water pump to allow liquid to be transferred from the pressure vessel to the water pump increases the volume of the portion of the working chamber that can contain gas, allowing the gas to expand. Alternatively, a working chamber can be considered to be defined by the pressure vessel and the portion of the water pump in fluidic communication with the pressure vessel (i.e. on one side of the working piston), and any conduit or other volume connecting the pressure vessel and the water pump. So defined, the working chamber has a variable volume, which volume can be changed by movement of the working piston. A portion of the variable volume can be occupied by liquid (e.g. water), while the remaining portion can be occupied by gas (e.g. air). The pressure of the gas contained in the working chamber is essentially equal to the pressure of any liquid contained in the working chamber, and to the pressure acting on the corresponding side or face of the working piston.

The compressor/expander device **320** may also include fins, dividers and/or trays **334** that can be positioned within the interior of the first and second pressure vessels **324**, **326**. The dividers **334** can increase the overall area within a pressure vessel that is in direct or indirect contact with air, which can improve heat transfer. The dividers **334** can provide for an increased heat transfer area with both air that is being compressed and air that is being expanded (either through an air/liquid interface area or air/divider interface), while allowing the exterior structure and overall shape and size of a pressure vessel to be optimized for other considerations, such as pressure limits and/or shipping size limitations.

In this embodiment, the dividers **334** are arranged in a stack configuration within the first and second pressure vessels **324** and **326**. Each divider **334** can be configured to retain a pocket of air. In one illustrative embodiment, each of the dividers **334** can include an upper wall, a downwardly extending side wall that may conform in shape and substantially in size to the inner wall of the pressure vessel, and an open bottom. The open bottom of each of the dividers **334** face in a common, substantially downward direction when the pressure vessel is oriented for operation. It is to be appreciated that although the figures show dividers that conform in size and shape to the interior of the pressure vessels **324**, **326**, and are generally shaped similarly to one another, other configurations are also

possible and contemplated, including embodiments that include dividers that are substantially smaller in width than the interior of a pressure vessel and/or that are shaped and sized differently than one another, among other configurations. Various other shapes and configurations of dividers can be used, such as, for example, the dividers that are shown and described in U.S. Provisional App. No. 61/216,942 and the Compressor and/or Expander Device applications incorporated by reference above. FIG. **4** illustrates another alternative embodiment of a divider that can be used. It is also to be appreciated that dividers may include fin structures (arrays of pins or rods, and other porous structures) that increase the area available for heat exchange as well as maximize the proximity of air to the dividers, and that dividers that do not retain a pocket of air are contemplated. In some embodiments, dividers can be structures that support a film of water. In some embodiments, rather than the dividers having an empty space between them, they can have intermediate structures between them, such as arrays of pins or rods, amorphous structures, porous structures, etc.

As shown in FIG. **3**, a manifold **336** can extend centrally through the stack of dividers **334** and fluidly couple each of the dividers **334** to an inlet/outlet port **338** of the pressure vessels **324**, **326**. In other embodiments, the manifold may include multiple tubes and/or may be located peripherally about the stack of dividers or in other positions. Air may enter and/or exit the pressure vessels **324**, **326** through the ports **338**, and can provide a conduit for fluid communication between pockets of air associated with each divider **334**. In other embodiments, such as those in which dividers do not retain a pocket of air, the manifold may not be included.

As discussed above, heat can be transferred from and/or to air that is compressed and/or expanded by liquid (e.g., water) within a pressure vessel. An air/liquid or air/divider interface (e.g., provided in part by dividers discussed above) may move and/or change shape during a compression and/or expansion process in a pressure vessel. This movement and/or shape change may provide a compressor/expander device with a heat transfer surface that can accommodate the changing shape of the internal areas of a pressure vessel through which heat is transferred during compression and/or expansion. In some embodiments, the liquid may allow the volume of air remaining in a pressure vessel after compression to be nearly eliminated or completely eliminated (i.e., zero clearance volume).

A liquid (such as water) can have a relatively high thermal capacity as compared to a gas (such as air) such that a transfer of heat energy from the gas to the liquid significantly decreases the temperature rise of the gas but incurs only a modest increase in the temperature of the liquid. This allows buffering of the system from substantial temperature changes. Heat that is transferred between the gas and liquid or components of the vessel itself may be moved from or to the pressure vessel through one or more heat exchangers that are in contact with the liquid or components of the vessel. One type of heat exchanger that can be used to accomplish this is a heat pipe, as discussed in greater detail below.

Thus, the liquid within a pressure vessel can be used to transfer heat from air that is compressed (or to air that is expanded) and can also act in combination with a heat exchanger to transfer heat to an external environment (or from an external environment). By way of example, as shown in FIG. **3**, a heat exchanger that includes a circular array of heat pipes **342** that extend through a wall of the pressure vessels **324** and **326** and can contact both the liquid within the vessels and the external environment. The heat pipes **342** are just one example embodiment of a type of heat exchanger that can be used to transfer heat to or from liquid of a pressure vessel. It should be understood that other types of heat exchangers and other heat pipe configurations can alternatively be used. For example, other heat management devices can be used (alternatively or in addition to) such as, for example, fins, pins, convection-inducing shapes, and/or swirl-inducing shapes, etc.

The embodiment of FIG. **3** is one example of an arrangement of pressure vessels and an actuator that can be used within an air compression and storage system. It should be understood, that other arrangements are also possible and contemplated. By way of example, although the actuator is shown as including a single, double acting piston that is oriented vertically, other embodiments may include housings with actuators that include horizontally oriented pistons and/or multiple hydraulic pistons that operate in parallel to move fluid within pressure vessels. According to some embodiments, actuators may lack pistons altogether and instead comprise pumps that move fluid into and out of the pressure vessels. Multiple pumps and/or pistons can additionally, or alternatively, be used in parallel to move fluid into and out of the pressure vessels, according to some embodiments. Still, according to other embodiments, an actuator, such as a hydraulic piston, may have a direct mechanical connection to the motor/generator of the system, as embodiments of the system are not limited to that shown in the figures.

FIGS. **5**A-**18** illustrate an example of a two-stage energy compression and expansion system **400**. FIG. **5**A is a schematic illustration of a portion of the system **400**. Stage one includes a pair of pressure vessels **424**, **426** connected in fluid communication to an actuator **412**. For example, various types of conduit or housing (as shown in FIG. **5**A) can be used to fluidically couple various components of the actuator **412** to the pressure vessels. The pressure vessels **424**, **426** can each include dividers or tray (not shown in FIG. **5**A) as described above for previous embodiments. The actuator **412** includes water pumps driven by hydraulic actuators or cylinders as described below. As shown in FIG. **5**A, the actuator **412** includes water pumps **444**A, **444**B and **446**. In this embodiment, water pumps **444**A and **444**B are constructed in two portions to reduce the height of the pumping equipment, and in this embodiment water pumps **444**A and **444**B act in concert as a single pump. Each of the water pumps **444**A, **444**B and **446** include a water piston, or working piston, that is hydraulically driven with a pair of hydraulic cylinders. Water pump **444**A is coupled to and driven by hydraulic cylinders **452** and **454**; water pump **444**B is coupled to and driven by hydraulic cylinders **456** and **458**; and water pump **446** is coupled to and driven by hydraulic cylinders **448** and **450**. A common drive rod couples the water pistons to their respective hydraulic cylinders. The hydraulic cylinders for stage one can all be controlled by a first high efficiency hydraulic pump **414** as shown in FIG. **5**B. A hydraulic pump/motor, such as, for example, an Artemis Digital Displacement hydraulic pump manufactured by Artemis Intelligent Power Ltd. can be used. Other examples of hydraulic pumps that can be used are described in U.S. Pat. No. 7,001,158, entitled "Digital Fluid Pump," and in U.S. Pat. No. 5,259,738, entitled "Fluid-Working Machine," the entire disclosures of which are hereby incorporated by reference.

As shown in FIG. **5**B, a system controller or hydraulic controller **416** can be used to operate and control the hydraulic pump/motor **414**. The hydraulic pump/motor **414** can be connected to each end of the hydraulic cylinders associated with the various water pumps (or working actuators) of the system. A valve is coupled between each end (i.e. each hydraulic chamber) of the hydraulic cylinders and the hydrau-

lic pump, which can be selectively opened and closed, e.g. under control of the hydraulic controller **416**, to fluidically couple or fluidically isolate, respectively, the output of the hydraulic pump **414** and each hydraulic chamber of each hydraulic cylinder to selectively actuate a specific hydraulic cylinder and, more particularly, a particular side (e.g., blind side and/or rod side, as described in more detail below) of the hydraulic piston in the specific hydraulic cylinder. Each valve is designated by **418** in FIG. **5**B.

As shown in FIG. **5**A, stage two of the system **400** includes a pair of pressure vessels **462** and **464** connected in fluid communication to an actuator **413** that includes water pumps **466** and **468**. As with the stage one configuration, each of the pressure vessels **462** and **464** can include dividers and each of the water pumps **466** and **468** include a water piston that is hydraulically driven by (or, in expansion mode, drives) a pair of hydraulic cylinders, also shown in FIG. **5**A. Water pump **466** is coupled to and driven by hydraulic cylinders **470** and **472** and water pump **468** is coupled to and driven by hydraulic cylinders **474** and **476**. The hydraulic cylinders for stage two can all be driven by, or drive a second high efficiency hydraulic pump/motor (not shown) in a similar fashion as stage one, using the same hydraulic controller **416**, or a second hydraulic controller (not shown). It is to be appreciated that the stage two hydraulic cylinders, can be driven by, or drive various configurations of hydraulic pump/motor, and that the system **400** can have, for example, one, two, three, four, or more hydraulic pump/motors.

Each of the first and second pressure vessels **424** and **426** of the first stage are fluidly coupled to the pressure vessels **462** and **464** of the second stage by a conduit that may include one or more valves (not shown in FIG. **5**A) to selectively open and close fluid communication between the volumes of the corresponding pressure vessels. The first and second pressure vessels **424** and **426** of stage one can also each include a valve (not shown) that opens to allow the receipt of air from the environment (e.g., at atmospheric pressure) or air that has been optionally pre-compressed from atmospheric pressure to a desired pressure, for example, 1-3 bar. Additional valves can be used between the pressure vessels of stage two and a storage structure or cavern (not shown) in which the compressed air from the system may be stored. Valves can be coupled to and disposed at locations along the conduit connecting the various components or directly to the components.

FIG. **6**A schematically illustrates the various components of a portion of actuator **412** including the water pump **446**, and its corresponding hydraulic cylinders **448** and **450**; and FIG. **6**B schematically illustrates the various components of the hydraulic cylinder **448**. It should be understood, however, that each of the water pumps and hydraulic cylinders in both the first stage and the second stage of the system **400** can be similarly constructed and function in the same manner as water pump **446** and hydraulic cylinder **448**. As shown in FIG. **6**A, the water pump **446** includes a cylindrical water reservoir or housing **482** that can contain liquid, such as, for example, water W (though other working liquids could be used), a water piston, or working piston, **474** and a drive rod **476** coupled to the piston **474**. The drive rod **476** is also coupled to hydraulic drive pistons **478** and **480** of the hydraulic cylinders **448** and **450**, respectively. Thus, the hydraulic cylinders **448** and **450** can be used to operate or drive the piston **474** back and forth within the housing **482**, pressurizing and moving the water W contained therein. The water housing **482** is divided into two portions, one on each side of piston **474**. Each portion is in fluid communication with a pressure vessel, such as the pressure vessels described above (not shown in FIG. **6**A). As described above, each side of working piston **474** bears the same pressure as that of the gas contained in the pressure vessel with which that side of working piston **474** bounds a working chamber containing the air.

FIG. **6**B schematically illustrates the hydraulic cylinder **448**. As shown in FIG. **6**B, the hydraulic cylinder **448** includes a cylindrical housing **484** in which a hydraulic drive piston **478** is movably disposed. As stated above, the drive piston **478** is coupled to the drive rod **476**. Within the housing **484** of the hydraulic cylinder **448**, hydraulic fluid Hf can be pumped in and out, as will be described in more detail below.

The housing **484** of the hydraulic cylinder **448** defines an interior volume that is divided into two portions at any given time during a stroke of the hydraulic cylinder by the drive piston or hydraulic piston **478**. As shown in FIG. **6**B, the portion of the interior volume within the housing **484** above the drive piston **478** (or on the opposite side of the piston **478** from the rod **476**) is referred to herein as the "blind side" or "bore side" Bs, and the portion of the interior volume within the housing **484** shown below the drive piston **478** (or on the same side as the rod **476**) is referred to herein as the rod side Rs. To drive the hydraulic cylinders, hydraulic fluid Hf can be pumped into each hydraulic cylinder on either (or both) sides of the drive piston to achieve varying pressures and flow rates within the system. For example, at various steps in the process of compressing air for energy storage, the pressurized hydraulic fluid Hf can be pumped into the housing **484** only on the blind side Bs, only on the rod side Rs, or on both sides, depending on the desired output pressure, flow rate and/or direction of force desired at the various steps of a compression or expansion cycle.

For example, referring to the water pump **446** and its associated hydraulic cylinders **448** and **450**, to move the working piston **474** within the housing **482** to change the volume of the working chamber bounded in part by the working piston, one or both of the hydraulic cylinders **448** and **450** can be actuated at a given time period to provide the desired force to move the piston. For example, to move the piston **474** upward, hydraulic fluid can be pumped into the blind side, or both the blind side and the rod side of the hydraulic cylinder **450**, or hydraulic fluid can be pumped into the rod side of the hydraulic cylinder **448**, or a combination thereof. To move the piston **474** downward, hydraulic fluid can be pumped into the blind side of hydraulic cylinder **448**, both the blind side and the rod side of the hydraulic cylinder **448**, or the rod side of the hydraulic cylinder **450**, or a combination thereof. Each of these modes has a different total area of hydraulic piston bearing the pressure of the hydraulic fluid, and thus will exert a different force on the working piston **474**. It is to be appreciated that varying the pressure of the hydraulic fluid can act in concert with the varying combinations of reservoir pressurization to provide a wide range of force to move the piston.

The system **400** can be configured to operate within a desired energy efficiency range of the hydraulic pump(s). The operating pressure range of the hydraulic pump(s) and the ratio of surface areas of the water pistons to the hydraulic drive pistons (also referred to herein as "piston ratio") can be used to determine an optimal operating sequence for the compression process. In addition, by varying which hydraulic pump(s) is actuated to move a water piston at a particular point in the cycle, the pressure in the system can be further varied. The pump has a preferred range of pressure and flow, within which it can be continuously operated as the air piston strokes.

As shown, for example, in FIGS. **6**C-**6**F, the water piston **474** has an operating surface **490** that has a surface area SA_w that is the same on both sides of the water piston (i.e. the

annular area bounded by the outer perimeter of the water piston **474** and the outer perimeter of the rod **476**), and the hydraulic drive piston **478** has an operating surface **492** on the blind side with surface area SA_b (i.e. the circular surface area bounded only by the outer perimeter of the hydraulic drive piston) and an operating surface **494** on the rod side with a surface area SA_r (i.e. the annular area bounded by the outer perimeter of the hydraulic drive piston and the outer perimeter of the rod). The operating surface area of a piston is the surface area of the piston on which force is exerted by hydraulic fluid pressure. Thus, when a hydraulic cylinder is actuated by communicating pressurized hydraulic fluid to the blind side, the effective surface area of the hydraulic piston is greater than when the same pressure is communicated to the rod side (i.e., $SA_b>SA_r$). Thus, for a given hydraulic fluid pressure, more force is applied to the rod **476** (albeit in different directions) when the hydraulic fluid pressure is applied to the blind side than when it is applied to the rod side. It is also possible to generate yet a different amount of force for a given hydraulic pressure by applying the hydraulic fluid pressure to both sides of a piston. In this mode of operation, referred to as a regenerative mode, the net piston area is equal to the difference between the blind side area SA_b and the rod side area SA_r. This net area corresponds to the cross-sectional area of the rod, and is referred to as $SA_{(b-r)}$.

In some embodiments, a combination of surface areas associated with hydraulic drive piston **478** and hydraulic drive piston **480** are pressurized to achieve a desired output force on rod **476**, which may correspond to a second pressure of water W. The effective or net operating surface area A_{net} being pressurized for a given gear is then equal to the sum of the surface areas associated with the various portions of the hydraulic cylinders **448** and **450** being pressurized with hydraulic fluid. The sum of the surface areas can also be referred to as the surface area of the hydraulic piston(s) SA_h. It is to be appreciated that other embodiments include those in which the hydraulic fluid pressure communicated to the various surface areas in actuator **412** may be different from each other.

The ratio of the surface area of the working piston or water piston SA_w to the surface area of the hydraulic piston(s) SA_h dictates the hydraulic pressure needed to achieve a desired water pressure, and thus gas pressure, at a given point in the cycle. By varying the surface area ratio for a given water pump/hydraulic cylinder set, varying levels of water pressure can be achieved at different points within the compression cycle for the same levels of hydraulic pressure. The pressure of the hydraulic fluid needed to achieve a particular water pressure (and/or air pressure) can be calculated as follows.

$$F_h(\text{force of hydraulic fluid})=P_h(\text{hydraulic pressure})\times SA_h(SA_r \text{ or } SA_b \text{ or } SA_{(b-r)})$$

$$F_w(\text{force applied to water})=P^w(\text{water pressure})\times SA_w$$

$$F_h=F_w$$

$$P_w\times SA_w=P_h\times SA_h$$

$$P_w=P_h\times(SA_h/SA_w) \text{ and } P_h=P_w\times(SA_w/SA_h)$$

A maximum and minimum operating pressure for each hydraulic pump can be established, e.g. as the limits of a range of operating pressure within which the hydraulic pump operates at or above a desired energy efficiency. This pressure range can be used to determine the piston ratio (e.g., (SA_h/SA_w)) needed at various points during a compression cycle to operate the system so as to approach or achieve operation within the maximum efficiency range of the hydraulic pump. For example, for a hydraulic pump having a maximum efficient operating pressure of 300 bar and a desired maximum output pressure of the air (and therefore the water) is 30 bar, the piston ratio (i.e., (SA_w/SA_h)) required at the end of the pressurization cycle, when the water and air pressure reaches 30 bar, is 10:1. Correspondingly, if the hydraulic pump has a minimum efficient operating pressure of 120 bar, and the air enters the system at 3 bar, then the piston ratio (i.e., (SA_w/SA_h)) required at the start of the pressurization cycle, when the water and air pressure is 3 bar, is 40:1. The number of water pumps and hydraulic pumps needed, and the piston ratios (and corresponding size of the hydraulic cylinders and water pumps) for the various water pump/hydraulic sets can then be determined such that the system can operate within the desired efficiency range for the entire compression cycle (i.e., compressing the air from 3 bar to 30 bar). There are a variety of different operating sequences that can be used to incrementally increase the pressure in the system and to achieve this output. It is understood that the approach can be applied using hydraulic pumps with maximum operating pressures higher or lower than 300 bar, and minimum operating pressures higher or lower than 120 bar.

At a given time during a compression or expansion cycle, the actuator **412** can be referred to as being in a particular "state" or gear that is associated with the piston area ratios being pressurized within the actuator at that time. As described above, when the system makes a change in the ratio of the pressure of the hydraulic fluid in the hydraulic actuator to the pressure of the water in the water pump(s) actuated by the hydraulic actuator (i.e., the ratio of the pressurized surface area of the water piston to the net operating pressurized surface area(s) of the hydraulic piston(s) actuating the water piston) this is referred to as a "gear shift" or "gear change." There is a variety of different combinations or sequences of gear changes (changes in piston area ratios) that can be incorporated into a particular operating sequence of the system.

In the example of system **400**, where each water pump has two identical associated hydraulic cylinders to actuate the water pump, there are sixteen possible states for the two actuators, i.e. every combination of each chamber being pressurized or not pressurized (two states for four chambers gives 2^4 combinations). For identical hydraulic cylinders (i.e. in which the blind side area of each cylinder is the same and the rod side area of each cylinder is the same), there are four different possible gears (with associated piston area ratios) that can be used to actuate each working or water piston in each direction. For example, to move a water piston upward in one water pump, hydraulic fluid can be pumped into (1) the rod side of the upper hydraulic cylinder (or the rod side of the upper hydraulic cylinder and the blind side of both cylinders, which cancel each other out), (2) the blind side of the lower hydraulic cylinder (or the blind side of the lower cylinder and the rod side of both cylinders, which cancel each other out), (3) both the blind side and the rod side of the lower hydraulic cylinder, or (4) both the rod side of the upper hydraulic cylinder and the blind side of the lower hydraulic cylinder. The state in which none of the chambers is pressurized does not produce any force on the working piston, nor (for identical cylinders) does the state in which all chambers are pressurized. In the embodiment depicted in FIG. **5**A, each stage is configured with two water pumps that actuate one after the other, and because each water pump in this embodiment has four possible gears, the compression process has eight possible gears. It is to be appreciated that other embodiments include those in which the hydraulic fluid pressure communicated to the various surface areas in actuator **412** may be different from each other and may create more than four

possible gears in each water pump. It is appreciated that given an actuator that can achieve four possible gears, it may be preferable to use fewer gears than four gears, for example three gears. The reasons for such a preference may involve the dynamic response of the fluid and/or mechanical components to the gear shift events. Correspondingly, an embodiment configured with two water pumps may be operated using five, six, or seven of the possible eight gears. Moreover, the compression process may also vary according to the current pressure of the compressed air storage vessel, e.g. when the storage vessel is at relatively low pressure, the preferred compression process may use one, two, three, four, five, six, or seven of the possible eight gears.

In other embodiments, an actuator can be configured to have a different number of possible different gears and gear changes based on, for example, the number of hydraulic cylinders, the size (e.g., diameter) of the housing of a hydraulic cylinder in which a hydraulic piston is movably disposed, the size (e.g., diameter) of the hydraulic pistons disposed within the housing of the hydraulic cylinders, the number and size of drive rods coupled to the hydraulic pistons, and/or the size of the working piston to be actuated. Further examples of actuators are described below with reference to FIGS. **51**A-**51**D, **52**A-**52**C, **53**, **54**A-**54**B, **55** and **56**.

Thus, the hydraulic pressure time profile can be varied as needed to achieve a particular output air pressure. The efficiency range of the hydraulic pump system can determine the number of gears and gear shifts that may be needed for a desired air pressure range (difference between input or start pressure and output or end pressure). For example, if the hydraulic pump's efficiency range is narrower, then more gears may be needed for a given air pressure range. The size and number of gears can also depend on the particular operating speed (RPM) of the system.

FIGS. **7-14** illustrate an air compression cycle using the system **400** and operating the system within or approaching the maximum (or a desired) efficiency range throughout the stroke or cycle of the system. The optimization process in this example utilizes an operating regime that includes four different gears for each stage in the process to maintain operation within the optimal efficiency range of the hydraulic system. In this example, the four gear modes are accomplished by using two water pumps in sequence, each of which uses two or three gears. The system **400** can be configured, for example, to compress air from 3 bar to 30 bar in stage one, and then from 30 bar to 180 bar in stage two. It should be understood that this is only one example operating sequence that can be used. The water pressure, and therefore the air pressure, in the system can be gradually ramped up during a given cycle. As the system moves through each of the various gear shifts, the pressure of the hydraulic fluid increases from a minimum efficient operating pressure of the hydraulic system (e.g., 120 bar) to the maximum efficient operating pressure of the hydraulic system (e.g., 300 bar). As the maximum desired operating pressure of the hydraulic pump/motor is reached within each gear mode of the cycle, the system shifts to the next gear in the sequence.

FIG. **7** includes reference numbers corresponding to the various components of the system **400** as described above and includes conduit or housing connecting the various water pumps and pressure vessels. Although not visibly shown in FIGS. **7-14**, the lower hydraulic cylinders **450**, **454**, **458** of stage one are each shrouded inside a support housing that is labeled so as to indicate the hydraulic cylinders the housing encases.

FIG. **7** illustrates a starting condition for a compression cycle that includes receiving air directly from the outside environment (i.e. at ambient pressure) or from a pre-compressor (e.g. at 3 bar) into the first pressure vessel **424** of the first stage. FIGS. **8-10** and **12-14** illustrate the flow of water and air and the drive direction for the hydraulic cylinders of both stage one and stage two of the compression cycle of the system. FIGS. **11-14** illustrate a full cycle for compressing air received within the second pressure vessel **426** of the first stage. Thus, FIG. **11** illustrates an end of the cycle to compress air initially received in the first pressure vessel **424** and also a starting point for a cycle that includes compressing air initially received within the second pressure vessel **426**. One full cycle of the system **400** (FIGS. **7-11** or FIGS. **11-14**) can be, for example, a total of 6 seconds.

As shown in the example of FIG. **7**, a compression cycle involves both stage one and stage two, and can begin, for purposes of illustration, in the following state: with the first pressure vessel **424** of stage one and the second pressure vessel **462** of stage two each filled with water, and the second pressure vessel **426** of stage one and the first pressure vessel **464** of stage two each filled with air. A compression stroke will commence by driving water pumps **444**A and **444**B of stage one and driving water pump **466** of stage two. A valve (not shown) between the stage one first pressure vessel **424** and a pre-compressor (not shown) can be opened to allow intake air to enter the conduit connected to the pressure vessel **424**. A valve (not shown) between the stage one second pressure vessel **426** and the stage two second pressure vessel **462** can be opened to allow fluid communication between the two pressure vessels. A valve (not shown) between the stage two first pressure vessel **464** and the storage cavern (not shown) can be closed at the beginning of the compression stroke and can be opened at some time during the compression stroke, for example when the air pressure in pressure vessel **464** is substantially equal to the storage cavern (not shown) air pressure.

It is important to recognize that the system operates three air manipulation processes in concert: one intake process and two compression processes. Therefore, there are three air volumes to recognize. During all compression strokes, there is one volume of air being drawn into the system at a substantially constant intake pressure, and there are two volumes of air, at two different pressures, compressing simultaneously. For example, while a first volume of air is being taken in at a substantially constant pressure of, for example, 3 bar, a second volume of air is being compressed from, for example, 3 bar to 30 bar, a third volume of air is being compressed from, for example, 30 bar to the discharge pressure (which varies with cavern pressure), for example 180 bar. FIG. **8** depicts the compression stroke approximately half way through the simultaneous actuation of water pumps **444**A and **444**B, and water pump **466**. With reference to FIG. **8**, a first volume of air at an intake pressure enters pressure vessel **424**, a second volume of air begins compression and transfer from pressure vessel **426** to pressure vessel **462**, and a third volume of air begins compression and transfer from pressure vessel **464** to the storage cavern (not shown). Note that FIG. **8** depicts an example and a condition in which the air pressure in pressure vessel **464** has achieved equality with the air pressure in the storage cavern and therefore a valve (not shown) between pressure vessel **464** and the storage cavern has been opened so as to allow air to be transferred from pressure vessel **464** to the storage cavern. It is recognized that in the course of air transfer from pressure vessel **464** to the storage cavern, a concomitant air compression may occur; the pressure increase thereof may be dictated by the relative volumes of pressure vessel **464** and the storage cavern.

FIGS. **8** and **9** illustrate a beginning portion of the compression cycle. Because the air is at relatively low pressure during the beginning portion of the compression cycle relative to the higher air pressures developed as the air compression proceeds, the beginning of the compression cycle uses the "high end" of the six gear sequence, and proceeds to using the "low end" of the six gear sequence. FIGS. **8** and **9** may include a gear shift from sixth gear to a next "lowest" gear, in this example a "fifth" gear, and may also include a gear shift from fifth gear to yet a next lowest gear, in this example a "fourth" gear. With respect to the air, water, and piston motions depicted in FIG. **8**, in stage one, the sixth gear can include actuating the hydraulic valves (not shown) to fluidically couple the pressurized hydraulic fluid output by the hydraulic pump/motor (not shown) to the rod side chamber and blind side chamber of the upper hydraulic cylinder **452** and to the rod side chamber and blind side chamber of the lower hydraulic cylinder **458**, and pumping the pressurized hydraulic fluid into those chambers. This will cause the piston in water pump **444**A to be moved downward, and the piston in water pump **444**B to be moved upward, by the respective actuators. In stage two, sixth gear can include actuating the hydraulic valves (not shown) to fluidically couple the pressurized hydraulic fluid output by the hydraulic pump/motor (not shown) to the rod side chamber and blind side chamber of the lower hydraulic cylinder **472**. This will cause the piston in water pump **466** to be moved upward by its actuator.

Before the pistons **444**A and **444**B, and **466** reach the end of their strokes (as shown in FIG. **9**), gear shifts from sixth to fifth, and from fifth to fourth, and from fourth to third may have been initiated. (Note that FIG. **9** depicts both the end of fourth gear and/or the beginning of third gear.) If a gear shift from sixth to fifth is initiated, the valves (not shown) that supply pressurized hydraulic fluid from the hydraulic pump/motor to the rod side chambers of hydraulic cylinders **454** and **456**, and **470** are opened. Opening these valves augments the piston rod "push" already coming from hydraulic cylinders **452** and **458**, and **472**, with a piston rod "pull" from hydraulic cylinders **454** and **456**, and **470**. It is to be appreciated that the sequence described above corresponds to an embodiment in which $SA_r<SA_{(b-r)}$, and that embodiments in which the surface areas are of a different relative sizes, for example, $SA_r>SA_{(b-r)}$, the pressurization combination that achieves sixth gear versus fifth gear can vary, and thus the preferred pressurization sequence can vary.

It is appreciated, and will be familiar to those skilled in the art, that in addition to valves that allow fluidic communication with a supply of pressurized fluid, all hydraulic cylinder chambers may also be provisioned with valves (not shown) that may allow fluidic communication with a low pressure hydraulic fluid reservoir (not shown), and that when these valves open, the associated hydraulic chamber fluid substantially maintains the low pressure of the hydraulic reservoir, and that hydraulic fluid can flow, which can allow hydraulic piston motion. Gear shift descriptions involving opening or closing valves communicating with pressurized hydraulic fluid, purposely omit, for brevity, detailing the associated closing or opening of valves that communicate between the cylinder chambers and the low pressure hydraulic fluid reservoir.

It is important to recognize that the timing of the gear shifts during compression of stage one are independent of the timing of the gear shifts in stage two. The preferred method of gear shift operation primarily attends to selecting gears that result in pressurized hydraulic fluid pressures that maximize the hydraulic pump operation energy efficiency. The hydraulic fluid pressures that drive each stage of compression against a first air pressure developing in the first stage of compression, and against a second air pressure developing in a second stage of compression, may differ, and that first air pressure differs from the second air pressure. In the preferred embodiment, the pressure of the pressurized hydraulic fluid that drives stage one is controlled independently from the pressure of the pressurized hydraulic fluid that drives stage two, and this may be achieved by provisioning each of stage one and stage two with a dedicated hydraulic pump/motor. It is recognized that in some embodiments, the pressure of the pressurized hydraulic fluid that drives stage one may be the same pressure as the pressure of the pressurized hydraulic fluid that drives stage two, and this may be achieved by provisioning both stages with a single hydraulic pump/motor.

The previous description and the following description is based on a compression process configured as a gear system with six available gears, where the sixth gear has the largest ratio of effective water piston surface area to effective hydraulic fluid surface area; in other words, in sixth gear the flow of a relatively small volume of hydraulic fluid will create a relatively large volume of water flow, and thus a relatively large change in volume available to be occupied by the gas being compressed. It is important to recognize that the first stage of the system is configured with a first set of six gear ratios, and that the second stage of the system is configured with a second set of six gear ratios. The six gears may be implemented using two, three, or more water pumps. It is also important to recognize that the first stage of compression operates at an air pressure range that is lower than the air pressure range operated in the second stage of compression. Correspondingly, the system is configured such that the six gear range used to drive the first stage of compression consists of gear ratios that are higher than the six gear range configured to drive the second stage of compression. It is appreciated, and it is anticipated, that embodiments can have more gears or fewer gears. It is appreciated, and it is anticipated, that embodiments can use more water pumps, or can use fewer water pumps.

With reference to FIGS. **7**-**9**, before the pistons **444**A and **444**B, and **466** reach the end of their strokes (as shown in FIG. **9**), gear shifts from sixth to fifth, and from fifth to fourth, and from fourth to third may have been initiated.

If a gear shift from fifth to fourth is initiated, the valves (not shown) that supply pressurized hydraulic fluid from the hydraulic pump/motor to the rod side chambers of hydraulic cylinders **452** and **458**, and **472** are closed. Closing these valves increases the piston rod "push" already coming from hydraulic cylinders **452** and **458**, and **472**, by leaving only the blind side chambers of hydraulic cylinders **452** and **458**, and **472** in fluidic communication with the pressurized hydraulic fluid. The increased piston rod "push" combines with the ongoing piston rod "pull" from hydraulic cylinders **454** and **456**, and **470** to achieve a fourth gear piston rod force that can be greater than the fifth gear piston rod force. The fourth gear piston rod force must be sufficient to achieve the water pump position depicted in FIG. **9**.

FIG. **10** depicts the action of the second water pumps of both stage one and stage two. Regarding the action of the second water pumps, FIG. **9** depicts third gear. Before the pistons **446**, and **468** reach the end of their strokes (as shown in FIG. **11**), gear shifts from third to second, and second to first may have been initiated. To configure the second water pumps in third gear, the valves (not shown) that supply pressurized hydraulic fluid from the hydraulic pump/motor to the rod side chambers and the blind side chambers of hydraulic cylinders **450** and **474** are opened, configuring cylinders **450** and **474** so as to "push" in regenerative mode.

If a gear shift third to second is initiated, the valves (not shown) that supply pressurized hydraulic fluid from the hydraulic pump/motor to the rod side chambers of hydraulic cylinders **448** and **476** are opened. Opening these valves results in augmenting the piston rod "push" already applied by hydraulic cylinders **450** and **474**, with a piston rod "pull" from hydraulic cylinders **448** and **476**. It is to be appreciated that the sequence described above corresponds to an embodiment in which $SA_r<SA_{(b-r)}$, and that embodiments in which the surface areas are of a different relative sizes, for example, $SA_r>SA_{(b-r)}$, the pressurization combination that achieves sixth gear versus fifth gear can vary, and thus the preferred pressurization sequence can vary.

If a gear shift from second to first is initiated, the valves (not shown) that supply pressurized hydraulic fluid from the hydraulic pump/motor to the rod side chambers of hydraulic cylinders **450** and **474** are closed. Closing these valves increases the piston rod "push" already coming from hydraulic cylinders **450** and **474**, by leaving only the blind side chambers of hydraulic cylinders **450** and **474** in fluidic communication with the pressurized hydraulic fluid. The increased piston rod "push" combines with the ongoing piston rod "pull" from hydraulic cylinders **448** and **476** to achieve a first gear piston rod force that can be greater than the second gear piston rod force. The first gear piston rod force must be sufficient to achieve the water pump position depicted in FIG. **11**.

As illustrated by the flow arrows for water and air in FIGS. **8-9**, as the system cycles through a first portion of a stroke, the water in the stage one first pressure vessel **424** will move and be drawn into the water pumps **444**A and **444**B as indicated by the water flow arrows. As the water flows out of pressure vessel **424**, volume is created inside the pressure vessel **424** for air to enter as indicated by the air flow arrows. For example, a relatively negative pressure can be created within the pressure vessel **424**, which will draw ambient air or pre-compressed intake air into the first pressure vessel **424**, and into pockets within each of the dividers within the pressure vessel **424**. It is understood that other embodiments may use dividers that do not include pockets. This results in air/liquid and air/divider interfaces through which heat may be transferred. When the pistons in the water pumps **444**A and **444**B reach the end of their stroke (as shown in FIG. **9**), a second portion of a stroke, as depicted in FIG. **10**, draws additional water from pressure vessel **424** into the water pump **448**, and draws additional intake air into pressure vessel **424**. FIG. **11** depicts the end of water removal from pressure vessel **424**, which is also the end of the air intake stroke that draws air into pressure vessel **424**.

As illustrated by the flow arrows for water and air in FIGS. **8-9**, as the system cycles through a first portion of compression, the water in the stage two second pressure vessel **462** will move and be drawn into water pump **466**. As the water flows out of pressure vessel **462**, volume is created inside the pressure vessel **462** for air from pressure vessel **426** to enter as indicated by the air flow arrows in FIGS. **8** and **9**, urged by a relatively negative pressure that can be created within the pressure vessel **462**. When the piston in the water pump **466** reaches the end of its stroke (as shown in FIG. **9**), a second portion of a stroke, as depicted in FIG. **10**, draws additional water from pressure vessel **462** into the water pump **468**, which draws additional air into pressure vessel **462**. FIG. **11** depicts the end of water removal from pressure vessel **462**, which is also the end of the air compression and transfer stroke that draws air into pressure vessel **462**.

As illustrated by the flow arrows for water and air in FIGS. **8-9**, as the system cycles through a first portion of compression, water from water pump **466** will move into pressure vessel **464**. As the water flows into pressure vessel **464**, volume inside the pressure vessel **464** is reduced, increasing the air pressure in pressure vessel **464**. For example, when the air pressure inside pressure vessel **464** substantially equals the air pressure in the air storage cavern (not shown), a valve (not shown) may open between pressure vessel **464** and the storage cavern that establishes communication between pressure vessel **464** and the storage cavern. Water may continue to move from water pump **466** into pressure vessel **464**, which may transfer air from pressure vessel **464** into the air storage cavern as indicated by the air flow arrows in FIGS. **8** and **9**; urged by a relatively positive pressure that can be created within the pressure vessel **464**. When the piston in the water pump **466** reaches the end of its stroke (as shown in FIG. **9**), a second portion of a stroke, as depicted in FIG. **10**, moves additional water from water pump **468** into pressure vessel **464**, which moves additional air into the storage cavern (not shown). FIG. **11** depicts the end of water movement into pressure vessel **464**. It is appreciated that the valve that can establish communication between pressure vessel **464** and the storage cavern may open during the actuation of water pump **466** or during the actuation of water pump **468** as needed, for example, depending on when during the stroke the air pressure in pressure vessel **464** equals the air pressure in the storage cavern.

FIGS. **12** to **14** illustrate a similar process as described above, except that intake air is received in pressure vessel **426** (stage one), air is transferred from pressure vessel **424** (stage one) to pressure vessel **464** (stage **2**), and air is transferred from pressure vessel **462** (stage **2**) to the storage cavern (not shown). These processes operate in a similar manner as described above and are therefore not described in detail.

FIGS. **15-22** illustrate an expansion process using system **400**. Air that has been stored within the storage structure can be expanded through system **400** and be used to convert the stored energy into other forms that may be desirable, for example, it may be used to generate electricity. The various components of the system **400** can operate in a similar manner but in an opposite direction. Thus, air can be expanded through stage two and then stage one, in each stage the expanding air driving the pistons in the water pumps, which in turn drive the hydraulic pump/motor and the electric motor/generator to generate electricity. After the final expansion of the air inside a pressure vessel, if it is still above ambient pressure additional energy can be generated by expansion of the air by, for example, transferring the air to another energy conversion device, such as an air turbine. In other embodiments, after the final expansion inside a pressure vessel, the air may be released to the ambient environment, and may be released at substantially ambient air pressure.

FIG. **15** illustrates a starting condition for an expansion cycle that includes receiving compressed air from the storage cavern within the second pressure vessel **464** of the second stage. FIGS. **16-18** and **20-22** illustrate the flow of water and air and the drive direction for the hydraulic cylinders at both stage one and stage two for the expansion cycles of the system. Similar to FIG. **11**, FIG. **19** illustrates both an end of the cycle to expand air initially received in the second pressure vessel **464** and also a starting point for another cycle that includes expanding air initially received within the first pressure vessel **462** of stage two. One full cycle of the system **400** (FIGS. **15-19** or FIGS. **19-22**) can be, for example, a total of 6 seconds. The system can cycle in the same manner as described above for compression, but in an opposite direction of flow for water and air.

FIGS. **23-24** are example graphs illustrating the hydraulic fluid pressures and hydraulic fluid flow rates for one cycle (e.g., 6 seconds) of a system, such as system **400** configured to operate with a four gear sequence as described above, and configured to maintain compressed air within the storage cavern at 184 bar. FIG. **23** illustrates the hydraulic fluid pressures and fluid flow rates for stage one of the system and FIG. **24** illustrates the hydraulic fluid pressures and fluid flow rates for stage two of the system. The pressure and flow rate are shown for each of the four gear steps. These example charts illustrate gear shifts when the hydraulic fluid pressure reaches 360 bar. Immediately after each gear shift, the pressure drops to approximately 200 bar. It is understood that these pressures are examples only, and that other high and low pressure values may be selected. The values for high pressure and low pressure are selected according to the operating characteristics of the hydraulic pump/motor **414**. Hydraulic pumps operate relatively efficiently when they operate within a pressure range dictated by the hydraulic pump. To effectively apply the system and method, the pressures at which gear shifts occur, are selected with respect to the pressures at which the hydraulic pump operates efficiently. Typically, a hydraulic pump's energy efficiency is most sensitive to its output pressure, which is why the system and methods carefully attend to fluid pressure, but other pump characteristics must also be simultaneously attended to; particularly the pump's maximum flow rate in terms of fluid volume per unit time. It should be noted that some hydraulic pumps may have other constraints, for example, minimum flow rates.

It should be noted that gear shift points may also be constrained by other embodiment details such as the maximum extension position of a hydraulic cylinder. It should also be noted that a hydraulic pump's operating characteristics usually interact, and changes in pressure usually also create changes in flow rate. FIGS. **23** and **24** show one example of a hydraulic fluid pumping scenario that corresponds to a hydraulic pump having a maximum hydraulic fluid flow rate of approximately 7.6 gallons per second (gps). In this example, four of the possible six gears are used. In this example, several of the gear shifts involve pressure changing from 360 bar to about 200 bar, and in this example the pressure change is accompanied by a substantially simultaneous drop in fluid flow rate, to approximately 4.0 gps. The product of hydraulic fluid pressure and hydraulic fluid flow rate is power, and this example shows a pressure and flow scenario that maintains an approximately constant power value during operation of the pump system. Constant power is one method for selecting the relationship between output pressure and output flow rate. It is understood that other embodiments may choose to vary pressure and flow in a fashion that results in a power that is something other than constant.

FIGS. **25-26** are example graphs illustrating the hydraulic fluid pressures and hydraulic fluid flow rates for one cycle of a system, such as system **400**. The configuration of the system is such that the stage one operates using a four gear sequence as described above. FIG. **26** depicts a scenario in which stage two compresses air, and when the compressed air pressure substantially equals the air pressure in the storage cavern, the compressed air is pumped into a storage cavern currently at 90 bar. FIG. **25** illustrates the pressures and fluid flow rates for stage one of the system, and FIG. **26** illustrates the pressures and fluid flow rates for stage two of the system, and depicts how, in this scenario, the preferred gear shift sequence uses three of the possible six gears. The pressure and flow rate are shown for each of the four stage one gear steps, and for each of the three stage two gear steps. These example charts illustrate gear shifts occurring at points dictated by constraints other than hydraulic pump maximum pressure. For example, FIG. **26** shows a gear shift that occurs at a pressure of about 310 bar, which is less than the 360 bar maximum. This gear shift occurred because the first water pump reached the end of its stroke before the maximum hydraulic fluid pressure of 360 bar was called for. Further, the hydraulic fluid pressure during the operation of the second water pump remains below about 250 bar throughout the stroke of the second water pump. This is because the hydraulic fluid pressure called for to operate against the cavern's current pressure, using the highest gear available in the second water pump, is lower than the maximum hydraulic pump pressure. Importantly, the hydraulic fluid pressure remains within the hydraulic pump's efficient output pressure range, which in this example is between 120 bar and 360 bar. It is understood that the method may be applied using pressure ranges different from 120 bar to 360 bar.

FIGS. **27** and **28** are example graphs illustrating hydraulic pressure versus hydraulic pump volumetric flow capacity, for stage one and stage two for a system compressing air into a storage cavern at 90 bar and 180 bar, respectively.

FIGS. **29** and **30** are example graphs illustrating the power consumption of the hydraulic pumps used in a system, such as system **400** compressing air into a storage cavern currently at 90 bar. FIG. **29** illustrates the power consumption for stage one, and FIG. **30** illustrates the power consumption for stage two. FIGS. **31** and **32** are example graphs illustrating the power consumption of the hydraulic pumps used in a system, such as system **400** compressing air into a storage cavern currently at 180 bar. FIG. **31** illustrates the power consumption for stage one, and FIG. **32** illustrates the power consumption for stage two. As noted above, this example is one in which the power consumed by the pump (which is proportional to the hydraulic power produced by the pump) is maintained at an approximately constant level during operation of the system.

FIGS. **33-36** are example maps of the efficiency levels of the hydraulic pumps/motors used in a system, such as system **400**, when operated as hydraulic pumps at various pressures and speeds. The map is demarked into zones that depict the energy efficiency available for the hydraulic pumps. The systems and methods of operating the systems described herein can be configured to operate the hydraulic pump within the highest efficiency zone throughout the entire compression cycle. The efficiencies are determined based on a percentage of maximum volumetric displacement of the pump (which, for the pump used in the examples described above, can be selectively varied). For example, FIG. **33** illustrates efficiency based on 100% displacement for a flow rate of 7.6 gal./sec. FIG. **34** illustrates an efficiency based on 80% displacement, which means that the system is operating with a flow rate at 80% of the 7.6 gal./sec. (i.e., 6.0 gal./sec.). FIGS. **35** and **36** are similarly determined based on a 100% displacement at 7.6 gal./sec.

FIGS. **37-50** are example graphs illustrating various parameters of a system, such as system **400**, operating with a storage cavern pressure at 180 bar. FIGS. **37-42** illustrate various parameters associated with stage one, and FIGS. **43-47** illustrate various parameters associated with stage two. FIGS. **48** and **49** illustrate an example of how the associated pressures and flow rates during gear shifts throughout a cycle for an embodiment of a stage one and stage two change when using a different configuration of hydraulic cylinder piston surfaces areas. The nature of pressure and flow changes are seen by comparing FIGS. **48-49** with FIGS. **23-26**. FIG. **50** illustrates the hydraulic pressure versus volumetric flow

capacity of the system that corresponds to the pressure and flows depicted in FIGS. **48-49**.

As discussed above, heat can be transferred from air (or other gas) that is compressed in the pressure vessel to reduce the work consumed by the compression process. Heat can be transferred from air to a liquid, and/or air to dividers within the compression vessel, and/or from the liquid out of the pressure vessel. In some embodiments, to increase heat transfer, the system can be operated at a relatively slow speed. For example, in some embodiments, a complete compression or expansion cycle may be slow enough to provide additional time for heat transfer between the air and liquid. Enough heat energy may be transferred, according to some embodiments, to approximate an isothermal compression and/or expansion process, achieving work reduction or extraction and the efficiencies associated therewith. Additionally or alternatively, faster speeds may allow larger power levels to be achieved during expansion, isothermally or with temperature changes, which may be desirable at particular times during the system operation.

The use of a liquid (e.g. water) as a medium through which heat passes during compression and/or expansion may allow for a continuous temperature moderation process and may provide a mechanism by which heat may be moved in and/or out of the compression vessel. That is, during compression the liquid may receive heat from air that is being compressed, and pass this heat to the external environment continuously, or in batches, both while air is being compressed and while air is being received by the pressure vessel for later compression. Similarly, heat addition may occur when a compressor/expander device is operating in an expansion mode both during expansion and as expanded air is passed from a pressure vessel.

As discussed above, the liquid within a pressure vessel can be in contact with the air at one or more air/liquid interfaces and air/divider interfaces, across which heat is transferred from air that is compressed and/or to air that is expanded. The pressure vessel can also include a heat exchanger, such as one or more heat pipes as discussed above, that transfers heat between the liquid and an environment that is external to the device. Heat may be moved from air that is compressed and/or to air that is expanded to achieve isothermal or near isothermal compression and/or expansion processes.

FIGS. **51**A-**51**D, **52**A-**52**C, **53**, **54**A-**54**B, **55** and **56** each illustrate embodiments of a hydraulic drive system or actuator that can be used to selectively adjust the ratio of hydraulic fluid pressure to the pressure of fluid on a working piston that bounds a working chamber. For example, an actuator can be used to actuate a working piston within a compression and/or expansion device to compress or expand a gas (e.g., air). The compression and/or expansion device can include a reservoir or housing that can contain a gas, a liquid, and/or both a gas and a liquid. An actuator can include one or more states or gears as described above for previous embodiments, to control the movement of the working piston and to maintain a desired relationship between the pressure of fluid in the working chamber and the pressure of the hydraulic fluid in the actuator.

In the embodiment shown in FIG. **51**A, the actuator includes two hydraulic cylinders, each having a different diameter and a different size (e.g., diameter) hydraulic piston that can actuate (or be actuated by) a working piston (or other driven member) at different hydraulic pressures. Because of the different sized hydraulic pistons, the number of gears and gear shifts can be increased (as compared to the actuator **412** described above that included two hydraulic pistons having the same diameter) due to the various combinations of operating surface areas available to pressurize the hydraulic pistons on either side of the working piston. By having more gears and gear shifts, the hydraulic actuator can operate with a higher degree of pressure selectivity, and thereby possibly operate a pump/motor in a more efficient range of hydraulic pressure for a given range of fluid pressure in the working chamber, or can operate in the same range of hydraulic pressure with a wider range of working chamber pressure, and/or to more closely control the desired output (or input) pressure, flow rate and/or direction of force desired at different stages of operation of a water pump and/or a compression and/or expansion device or system.

FIG. **51**A schematically illustrates the various components of a portion of an actuator **712**. As shown in FIG. **51**A, the actuator **712** includes a hydraulic cylinder **748** and a hydraulic cylinder **750**. The hydraulic cylinder **748** includes a housing **784** and a hydraulic piston **778** movably disposed within an interior region defined by the housing **784**. The hydraulic cylinder **750** includes a housing **785** and a hydraulic piston **780** movably disposed within an interior region of the housing **785**.

The hydraulic piston **778** divides the interior region of housing **784** of the hydraulic cylinder **748** into two portions: a hydraulic fluid chamber C**1** above the hydraulic piston **778** and a hydraulic fluid chamber C**2** below the hydraulic piston **778**. Similarly, the hydraulic piston **790** divides the interior region of housing **785** of the hydraulic cylinder **750** into two portions: a hydraulic fluid chamber C**3** above the hydraulic piston **780** and a hydraulic fluid chamber C**4** below the hydraulic piston **780**. The hydraulic fluid chambers C**1** and C**2** can be referred to as the blind side and the rod side, respectively, of the hydraulic cylinder **748**, and the fluid chambers C**3** and C**4** can be referred to as the rod side and the blind side, respectively, of the hydraulic cylinder **750**.

The hydraulic piston **778** has an operating surface area A**1** on the side of the hydraulic piston **778** associated with fluid chamber C**1** (the blind side) and an operating surface area A**2** on the side associated with the fluid chamber C**2** (the rod side). The hydraulic piston **780** has an operating surface area A**3** on the side of the hydraulic piston **780** associated with the fluid chamber C**3** (the rod side) and an operating surface area A**4** on the side associated with fluid chamber C**4** (the blind side).

Thus, because of the different sized hydraulic pistons and/or the different sized drive rods R**1** and R**2**, the operating surface areas A**1** and A**2** of the hydraulic piston **778** are different than the operating surface areas A**3** and A**4** of the hydraulic piston **780**. For example, the rod side operating surface area A**2** of hydraulic piston **778** can be smaller than the rod side operating surface area A**3** of hydraulic piston **780**. It is appreciated that R**2** can be made bigger than R**1** to a degree that can make A**2** equal to A**3**, or A**2** greater than A**3**. In an example in which hydraulic piston **778** has a smaller diameter than hydraulic piston **780**, the blind side operating surface area A**1** of hydraulic piston **778** is smaller than the blind side operating surface area A**4** of hydraulic piston **780**.

The hydraulic piston **778** is coupled to a driven member (in this embodiment a working piston) **774** via a drive rod R**1** and the hydraulic piston **780** is coupled to the working piston **774** via a drive rod R**2**. The working piston **774** is movably disposed within a housing **782** having an interior region that is divided by the working piston **774** into two working chambers, WC**1** and WC**2**, each configured to contain a fluid (e.g., water and/or air). The drive rods R**1** and R**2** slidably extend though respective openings in the housing **782**, each of which can include a seal such that the drive rods R**1** and R**2** can move within the openings to actuate the working piston **774**, but

fluid cannot pass between the working chambers WC1, WC2 and the hydraulic fluid chambers C2 and C3, respectively. In this embodiment, a diameter of the drive rod R1 is less than a diameter of the drive rod R2 and a diameter of the hydraulic piston **778** is smaller than a diameter of the hydraulic piston **780**.

As described above for other embodiments, the actuator **712** can be operated in one of multiple different gears, or states at any given time period during a cycle of the actuator **712** by varying the effective piston ratio (e.g., the net operating surface area of the hydraulic pistons to the surface area of the driven member, e.g. working piston) during a cycle or stroke of the actuator **712**. For a given hydraulic fluid pressure, the pressure of a working fluid within the housing **782** can be varied by varying the net operating hydraulically pressurized area of the hydraulic pistons, for convenience the possible area variations can be referred to as "gears". Conversely, for a given working fluid pressure, the hydraulic fluid pressure can be varied, e.g. in an expansion cycle. The quantity and sequence of gears can be varied as desired to achieve a desired relationship between the pressure of the working fluid within the reservoir (which is essentially the same as the pressure of the fluid in the working chamber) and the hydraulic fluid pressure supplied from (or supplied to) the hydraulic pump/motor. Thus, the actuation of the working piston (whether driving gas compression or being driven by gas expansion) can be fine tuned by configuring an optimal gear sequence for a given stroke of the hydraulic actuator **712**. As previously described, the number of possible gears for a given actuator can be based on the number of hydraulic cylinders, the size of the pistons, the size of the drive rods and the size of the working piston. In this embodiment, because the pistons **778** and **780** have different diameters and the drive rods R1 and R2 have different diameters, the 16 possible states of the actuator (each of the four chambers can be pressurized or not pressurized) can define 15 possible gears for which the actuator **712** (since the state in which no chambers are pressurized does not produce any net hydraulic piston area). If the drive rods R1 and R2 have the same diameter, the number of possible gears is **14**, because when all of the chambers are pressurized, the resulting net operating surface area will be equal to zero, as described in more detail below.

FIGS. **51**B and **51**C each illustrate different possible gears in which the actuator **712** can operate. These gears are identified for ease of reference as D1-D7 and U1-U7, but this numbering scheme does not necessarily indicate that the states are in order of net surface area. FIG. **51**B illustrates gears of the actuator **712** in which the working piston **774** can be driven upward by the actuator **712** (or in which upward movement of the working piston can drive the actuator), and FIG. **51**C illustrates gears of the actuator **712** in which the working piston **774** can be driven downward by the actuator **712** (or in which downward movement of the working piston can drive the actuator). As shown in FIGS. **51**B and **51**C, for a given gear (e.g., D1-D7, U1-U7) of the actuator **712**, if a fluid chamber (e.g., C1, C2, C3, C4) is active, i.e. in fluidic communication with the high pressure side of the hydraulic pump/motor (either to receive, and be driven by, pressurized hydraulic fluid provided by the hydraulic pump/motor acting as a pump, or to provide pressurized hydraulic fluid to, and drive, the hydraulic pump/motor acting as a motor), it is shown un-shaded and if a fluid chamber is inactive, i.e. is fluidically isolated from the high pressure side of the hydraulic pump/motor, it is shown shaded (cross-hatched) for that particular gear.

FIG. **51**D is a table that includes information that corresponds to the various gears (e.g., D1-D7 and U1-U7) of the actuator **712** in FIGS. **51**B and **51**C. The table also shows a gear U8 (not shown in FIGS. **51**B and **51**C) in which all of the chambers C1-C4 are pressurized (described in more detail below). The table of FIG. **51**D also shows the associated chambers (C1-C4) of the actuator **712** that are active (in fluidic communication with the high pressure side of the hydraulic pump/motor) for each gear (D1-D7, U1-U8). Specifically, as shown in the table, for a particular gear, P indicates that a chamber (e.g., C1, C2, C3, C4) is pressurized (active), and N indicates that a chamber is not pressurized (inactive). The column labeled DIR indicates which direction a force will be exerted by an active hydraulic fluid chamber (e.g., C1-C4). For example, if only chamber C1 is active (in fluidic communication with the high pressure side of the hydraulic pump/motor), the resulting force on the driven member (e.g. working piston **747**) will be in a down direction, and if only chamber C2 is active, the resulting force will be in an up direction. It is understood that "pressurized" means at a first pressure that is relatively high with respect to a second pressure referred to a "not pressurized."

The net operating surface area A_{net} of the actuator **712** for a particular gear is equal to the total of the surface areas (e.g., A1, A2, A3, A4) associated with the chambers (C1-C4) that are active for that gear. For purposes of illustration, the sign convention used in this example refers to a force exerted on the surface areas A1 and A3 as being in a positive (+) direction, and a force exerted on the surface areas A2 and A4 as being in a negative (−) direction. Thus, in this example, considering the driven member to be working piston **774** operating in a compression mode, if the net operating surface area A_{net} is negative, the actuator **712** will cause the working piston **774** to move in the up direction (e.g., gears U1-U8), and if the net operating surface area is positive, the actuator **712** will cause the working piston **774** to move in the down direction. Conversely, if the driven member is working piston **774** operating in an expansion mode, when expanding gas drives working piston **774** in the up direction, gears U1-U8 will be operative so that the active hydraulic chambers associated with those gears to pressurize hydraulic fluid in those chambers and supply that fluid to, and drive in a motor mode, the hydraulic pump/motor.

The different gears can be activated by placing selected hydraulic fluid chambers (e.g., C1, C2, C3, and/or C4) of the actuator **712** into fluidic communication with hydraulic fluid at a working hydraulic pressure (such as supplied by a hydraulic pump/motor operating as a pump, or supplied by the hydraulic fluid chambers to the hydraulic pump/motor operating as a motor), and fluidically isolating the other chambers from the working hydraulic pressure. For example, one or more valves can be coupled to each of the chambers C1-C4 that can be selectively opened (e.g. by a hydraulic controller, as described above and as described below with reference to actuator **812** shown in FIG. **52**A) to establish fluidic communication with the high pressure side of the hydraulic pump/motor and to allow hydraulic fluid to be pumped into the chamber. Conversely, the one or more valves can be controlled to isolate the chamber(s) from the high pressure side of the hydraulic pump/motor and to establish fluidic communication with a low pressure reservoir of hydraulic fluid, e.g. to allow hydraulic fluid to be expelled or drained from the chamber as the associated piston moves to reduce the volume of the chamber. One or more gears can be actuated during a single cycle or stroke of the actuator **712** to achieve the desired output pressure of a fluid within the housing **782**. In addition, the order of the gears can be varied. Thus, although the gears are labeled D1-D7 and U1-U8 in the figures, the actuator **712** can cycle through one or more gears in

a variety of different combinations and orders. For example, in one cycle, the actuator **712** can be configured to cycle through gears D**7**, D**6**, D**2** and D**5**, to incrementally increase the pressure of the working fluid within the housing **782** during the cycle.

In one example, as shown in the table of FIG. **51**D, and referring to FIG. **51**C, to actuate the gear D**7**, hydraulic fluid at a working pressure is selectively communicated to the chamber C**1** and the chamber C**2** of the hydraulic cylinder **748** and will exert hydraulic pressure on surface areas A**1** and A**2** in a down and an up direction, respectively. Because the surface area A**1** is greater than the surface area A**2**, the net operating surface area A_{net} (A**1**−A**2**) will be positive, and the resulting hydraulic force will move the hydraulic piston **778** downward, which in turn will move the working piston **774** downward. In another example, to actuate the gear U**2**, hydraulic fluid at a working pressure is selectively communicated to the chamber C**2** and C**4**, as shown in FIG. **51**B, which will exert hydraulic pressure on surface areas A**2** and A**4** in an up direction, resulting in a net operating surface area A_{net} that is negative (A_{net}=−A**2**+−A**4**). Thus, the hydraulic force will move the hydraulic piston **778** upward, which in turn will move the working piston **774** upward.

Referring to gear U**8** in the table of FIG. **51**D (but not shown in FIGS. **51**B and **51**C), if hydraulic fluid at a working pressure is selectively communicated to all the chambers (C**1**-C**4**), hydraulic pressure will be exerted on surface areas A**1** and A**3** in a down direction (i.e., positive), and surface areas A**2** and A**4** in an up direction (i.e., negative) and the resulting net operating surface area will be A_{net}=A**1**−A**2**+A**3**−A**4**. Because the diameter of drive rod R**1** and the diameter of drive rod R**2** are different in this example embodiment, the resulting net operating area A_{net} will not be equal to zero; rather, there is a net operating surface area A_{net}, which is equal to the difference in the cross-sectional areas of the two rods. If the diameter of drive rod R**1** and the diameter of drive rod R**2** are equal, the resulting net operating surface area will be zero, and thus the force on the working piston will be zero.

The bottom row of the table of FIG. **51**D illustrates the possible gears associated with the actuator **712** if the blind side and rod side surface areas of the hydraulic piston **778** are the same as the blind side and rod side surface areas of the hydraulic piston **780**, respectively (i.e., diameter of piston **778**=diameter of piston **780**, A**4**=A**1**, A**2**=A**3** and R**1**=R**2**). Such an embodiment is similar to the actuator **412** described above. As shown in the table, and referring, for example, to gear D**1** in FIG. **51**C, in such an embodiment, if hydraulic fluid at a working pressure is selectively communicated to fluid chambers C**1**, C**3** and C**4**, because the pistons **778** and **780** are equal in this example, the hydraulic pressure exerted on surface areas A**1** and A**4** will cancel each other out, and the resulting net operating surface area A_{net} will be equal to surface area A**3**. This will cause the hydraulic piston **780** to move downward, which in turn will move the water piston **774** downward. In another example, if hydraulic fluid at a working pressure is selectively communicated to fluid chambers C**2** and C**3**, as shown in gear D**3** in FIG. **51**C, because the surface area A**1** equals the surface area A**3**, in this example, the resulting force on the water piston will be zero. As shown in the table, in this example (e.g., where piston **778**=piston **780**, and rod **2**=rod **3**), gear D**6** is the same as gear D**3**, and gear D**2** is the same as gear D**5**. Thus, the total number of different gears available for such an embodiment is equal to 8; 4 in an up direction and 4 in a down direction.

FIG. **52**A illustrates another embodiment of an actuator that can be used with the devices and systems described herein. This embodiment illustrates an actuator that can include multiple hydraulic cylinders operatively coupled on one end of a working piston and configured to actuate the working piston. FIG. **52**A illustrates two different sized hydraulic cylinders, each having different diameter hydraulic pistons. It should be understood, however, that more than two hydraulic cylinders can be used and/or one or more hydraulic cylinders can also be operatively coupled to the opposite end of the working piston.

Specifically, FIG. **52**A schematically illustrates the various components of a portion of an actuator **812**. As shown in FIG. **52**A, the actuator **812** includes a hydraulic cylinder **848** including a housing **884** that defines an interior region and a hydraulic piston **878** movably disposed within the interior region of the housing **884**, and a hydraulic cylinder **850** including a housing **885** and a hydraulic piston **880** movably disposed within the interior region of the housing **885**. A drive rod R**1** is coupled to the hydraulic piston **880** of the hydraulic cylinder **850** and the hydraulic piston **878** of the hydraulic cylinder **848**, and a drive rod R**2** is coupled to the hydraulic piston **880** of the hydraulic cylinder **850** and can be coupled to a working piston (not shown) disposed within a housing **882** configured to contain a volume of fluid, as described above for previous embodiments. In this example embodiment, the hydraulic piston **878** has a smaller diameter than the hydraulic piston **880** and a diameter of the hydraulic drive rod R**1** is greater than a diameter of the hydraulic drive rod R**2**. It should be understood, however, that the hydraulic piston **878** can alternatively be the same size as, or larger than, the hydraulic piston **880**. Similarly, the hydraulic drive rods R**1** and R**2** can alternatively be the same size, or the hydraulic drive rod R**2** can be greater than the hydraulic drive rod R**1**.

The housing **884** of the hydraulic cylinder **848** defines within its interior region a fluid chamber C**1** above the hydraulic piston **878** and a fluid chamber C**2** below the hydraulic piston **878**. Similarly, the housing **885** of the hydraulic cylinder **850** defines within its interior region a fluid chamber C**3** above the hydraulic piston **880** and a fluid chamber C**4** below the hydraulic piston **880**. In this embodiment, the fluid chambers C**1** and C**2** can be referred to as a blind side and a rod side, respectively, of the hydraulic cylinder **848**, and the fluid chambers C**3** and C**4** can be referred to as a first rod side and a second rod side, respectively, of the hydraulic cylinder **850**.

The hydraulic cylinder **848** is coupled to a hydraulic pump/motor **814** (or other suitable source of pressurized hydraulic fluid) via conduits **895**, and the hydraulic cylinder **850** is coupled to the hydraulic pump/motor **814** via conduits **896**. The hydraulic pump/motor **814** is coupled to a system controller **816** that can be used to operate and control the hydraulic pump/motor **814** as described for previous embodiments. A valve **898** is coupled between each chamber of the hydraulic cylinders **848** and **850** and the hydraulic pump/motor **814** that can be selectively opened and closed, e.g. under control of the system controller **816**, to fluidically couple or fluidically isolate, respectively, the high pressure side of the hydraulic pump/motor **814** to each chamber so that the system or hydraulic controller **816** can selectively actuate (supply pressurized hydraulic fluid to) one or both chambers of one or both of the hydraulic cylinders **848** and **850** in a similar manner as described above for previous embodiments.

The hydraulic piston **878** has an operating surface area A**1** on the side associated with fluid chamber C**1** (e.g., the blind side) and an operating surface area A**2** on the side associated with the fluid chamber C**2** (e.g., the rod side). The hydraulic piston **880** has an operating surface area A**3** on the side of the hydraulic piston **880** associated with the fluid chamber C**3**

(e.g., the first rod side) and an operating surface area A4 on the side associated with fluid chamber C4 (e.g., the second rod side).

In this example embodiment, and as shown in FIG. 52A, the operating surface areas A1 and A2 of the hydraulic piston 878 are, different than the operating surface areas A3 and A4 of the hydraulic piston 880. For example, the operating surface area A2 of hydraulic piston 878 is smaller than the operating surface areas A3 and A4 of hydraulic piston 880. The operating surface area A4 of hydraulic piston 880 is greater than the operating surface area A3 of hydraulic piston 880, and both are larger than the operating surface areas A1 and A2 of hydraulic piston 878.

FIGS. 52B and 52C each illustrate different possible states or gears (identified as D1-D7, U1-U7) in which the actuator 812 can operate. FIG. 52B illustrates gears of the actuator 812 in which the actuator 812 can move a working piston coupled to the drive rod R2 upward within the housing 882, and FIG. 52C illustrates gears in which the actuator 812 can move the working piston downward within the housing 882. As with the previous embodiment, for a particular gear (e.g., D1-D7, U1-U7) shown in FIGS. 52B and 52C, if a fluid chamber (e.g., C1, C2, C3, C4) is pressurized with hydraulic fluid, it is shown unshaded, and if the fluid chamber is not pressurized with hydraulic fluid it is shown shaded.

The different gears can be activated by selectively fluidically coupling a source of hydraulic fluid at a working hydraulic pressure (e.g. via the hydraulic pump/motor 814 described above) to one or more of the fluid chambers (e.g., C1, C2, C3, and/or C4) of the actuator 812, as described for previous embodiments. For example, a selected one or more of the valves 898 can be selectively opened to pump hydraulic fluid into one or more of the chambers and/or to drain hydraulic fluid out of one or more of the chambers (e.g., at the end of a stroke). One or more of the gears can be actuated during a given cycle of the actuator 812 to achieve a desired output pressure of the fluid within the housing 882. The order of the gears can also be varied. Thus, although the gears are labeled D1-D7 and U1-U7 in FIGS. 52B and 52C, the actuator 812 can cycle through one or more gears in a variety of different combinations and orders as described above for previous embodiments.

A net operating surface area A_{net} of a particular gear is equal to the total of the surface areas (e.g., A1, A2, A3, A4) associated with the chambers (e.g., C1-C4) that are pressurized for a given gear. As described above, in this example embodiment, one or more hydraulic cylinders can also optionally be coupled to an opposite end of the working piston. In such an embodiment, the net operating surface area A_{net} of a particular gear will also include the surface areas associated with pressurized chambers of the hydraulic cylinder(s) operating on the opposite end of the working piston in a similar manner as described above for actuator 712.

FIG. 53 illustrates a variation of the actuator 812 in which the drive rod connecting the actuator to a working piston is coupled to the smaller of two hydraulic pistons and the drive rods have the same diameter. The actuator 912 includes a hydraulic cylinder 948 including a housing 984 that defines an interior region and a hydraulic piston 978 movably disposed within the interior region of the housing 984, and a hydraulic cylinder 950 including a housing 985 and a hydraulic piston 980 movably disposed within the interior region of the housing 985. A drive rod R1 is coupled to the hydraulic piston 978 and the hydraulic piston 980, and a drive rod R2 is coupled to the hydraulic piston 980 and can be coupled to a working piston (not shown) disposed within a housing (not shown) as described above for previous embodiments. In this embodiment, a diameter of the hydraulic piston 978 is greater than a diameter of the hydraulic piston 980, and a diameter of the drive rod R1 is equal to a diameter of the drive rod R2.

The housing 984 of the hydraulic cylinder 948 defines within its interior region a fluid chamber C1 above the hydraulic piston 978 and a fluid chamber C2 below the hydraulic piston 978. The housing 985 of the hydraulic cylinder 950 defines within its interior region a fluid chamber C3 above the hydraulic piston 980 and a fluid chamber C4 below the hydraulic piston 980. The hydraulic piston 978 has an operating surface area A1 on the side associated with fluid chamber C1 and an operating surface area A2 on the side associated with the fluid chamber C2. The hydraulic piston 980 has an operating surface area A3 on the side of the hydraulic piston 980 associated with the fluid chamber C3 and an operating surface area A4 on the side associated with fluid chamber C4.

As with the previous embodiments, the actuator 912 can be operated in multiple different gears to move a working piston (not shown) within a housing (not shown). A net operating surface area A_{net} of a particular gear is equal to the total of the surface areas (e.g., A1, A2, A3, A4) associated with the chambers (e.g., C1-C4) that are pressurized for a given gear as previously described. One or more hydraulic cylinders can also optionally be coupled to an opposite end the working piston. In such an embodiment, the net operating surface area A_{net} of a particular gear will also include the surface areas associated with pressurized chambers of the hydraulic cylinder(s) operating on the opposite end of the working piston in a similar manner as described above for other embodiments.

FIGS. 54A and 54B illustrate yet another embodiment of an actuator that can be used with the devices and systems described herein. In this embodiment, the actuator can move from one gear to another without having to selectively open a valve. An actuator 1012 includes a hydraulic cylinder 1048 including a housing 1084 that defines an interior region and a hydraulic piston 1078 movably disposed within the interior region of the housing 1084, and a hydraulic cylinder 1050 including a housing 1085 and a hydraulic piston 1080 movably disposed within the interior region of the housing 1085. A hydraulic drive rod R1 is coupled to the hydraulic piston 1080 of the hydraulic cylinder 1050 and the hydraulic piston 1078 of the hydraulic cylinder 1048. A hydraulic drive rod R2 is coupled to the hydraulic piston 1080 of the hydraulic cylinder 1050 and is coupled to a working piston 1074 movably disposed within a housing 1082 configured to contain a volume of fluid therein, as described above for previous embodiments. In this embodiment, the housing 1084 of the hydraulic cylinder 1048 is in fluid communication with the housing 1085 of the hydraulic cylinder 1080 such that the hydraulic piston 1078 can move between the interior region of the housing 1084, as shown in FIG. 54B, and the interior region of the housing 1085 as shown in FIG. 54A.

When the hydraulic piston 1078 is disposed within the housing 1085 (as shown in FIG. 54A), a hydraulic fluid chamber C1 is defined collectively by the housing 1084 and the housing 1085 above the hydraulic piston 1078 and above the hydraulic piston 1080, and a hydraulic fluid chamber C2 is defined below the hydraulic piston 1080. When the hydraulic piston 1078 engages the housing 1084 (as shown in FIG. 54B), a hydraulic fluid chamber C3 is defined by the housing 1084 above the hydraulic piston 1078, a hydraulic fluid chamber C2 is defined below the hydraulic piston 1080 and a hydraulic fluid chamber C4 is defined above the hydraulic piston 1080 and below the hydraulic piston 1078. Thus, as the hydraulic piston 1078 moves between the hydraulic cylinders 1048 and 150, the hydraulic fluid chambers can be redefined.

When the hydraulic piston **1078** is disposed with the housing **1085** (as shown in FIG. **54**A), the fluid chamber C**1** can be referred to as a blind side of collectively the hydraulic cylinder **1048** and the hydraulic cylinder **1050**, and the fluid chamber C**2** can be referred to as the rod side of the hydraulic cylinder **1050**. When the hydraulic piston **1078** engages the housing **1084**, the fluid chamber C**3** can be referred to as the blind side of the hydraulic cylinder **1048**, the fluid chamber C**2** is still referred to as the rod side of hydraulic cylinder **1050**, and the fluid chamber C**4** can be referred to as a rod side of collectively the hydraulic cylinder **1048** and the hydraulic cylinder **1050**.

In this embodiment, the hydraulic piston **1078** has a smaller diameter than the hydraulic piston **1080** and a diameter of the hydraulic drive rod R**1** is equal to a diameter of the hydraulic drive rod R**2**. As with other embodiments described herein, the hydraulic pistons **1078** and **1080** can have other sizes relative to each other, and the drive rods R**1** and R**2** can have other sizes relative to each other. For example, the hydraulic piston **1078** can be larger than the hydraulic piston **1080**. In such an embodiment, the set of possible gears can be changed based on the relative sizes of the hydraulic pistons and/or the position of the hydraulic pistons relative to the working piston. The hydraulic piston **1078** has an operating surface area A**1** and an operating surface area A**2**, and the hydraulic piston **1080** has an operating surface area A**3** and an operating surface area A**4** as shown in FIGS. **54**A and **54**B.

As with the previous embodiments, the actuator **1012** can be operated in multiple different gears to move the working piston **1074** within the housing **1082**. A net operating surface area A_{net} of a particular gear is equal to the total of the surface areas (e.g., A**1**, A**2**, A**3**, A**4**) associated with the chambers (e.g., C**1**, C**2**, C**3**, C**4**) that are pressurized for a given gear as previously described. The different gears can be activated by selectively fluidically coupling a source of hydraulic fluid at a working hydraulic pressure (e.g. via a hydraulic pump) to one or more of the fluid chambers (e.g., C**1**, C**2**, C**3**, and/or C**4**) of the actuator **1012**, as described for previous embodiments. For example, as shown in FIGS. **54**A and **54**B, a conduit **1095** can be coupled to and in fluid communication with the interior region of housing **1084**, and conduits **1096** and **1097** can be coupled to and in fluid communication with the housing **1085**. Each of the conduits **1095**, **1096** and **1097** can be coupled to for example, a hydraulic pump (not shown) to supply pressurized hydraulic fluid. Valves **1098** can be coupled to the conduits **1095**, **1096** and **1097** and/or to the respective housings **1084**, **1085**, and used to selectively open fluid communication to the various fluid chambers of actuator **1012**.

In this example, the number of possible gears and gear shifts for the actuator **1012** also varies when the hydraulic piston **1078** engages the housing **1084**. Thus, during one cycle or stroke of the actuator **1012**, the possible number of gears will change. For example, when the hydraulic piston **1078** is disposed within the housing **1085**, there are four possible pressurization states (two chambers, each pressurized or not pressurized), so the number of possible gears is equal to three; one gear defined when hydraulic fluid is pumped into fluid chamber C**1**, one gear defined when hydraulic fluid is pumped into fluid chamber C**2**, and one gear defined when hydraulic fluid is pumped into both fluid chamber C**1** and C**2**. In one example gear, if fluid chamber C**1** is selectively fluidically coupled to a source of hydraulic fluid at a working hydraulic pressure via one or both of the conduits **1095** and **1096**, the net operating surface area A_{net} will be equal to (A**1**+A**3**−A**2**), and the resulting force will be in a direction to the right. If both the fluid chamber C**1** and the fluid chamber C**2** are selectively fluidically coupled to a source of hydraulic fluid at a working hydraulic pressure, the net operating surface area A_{net} will be equal to (A**1**+A**3**−A**2**−A**4**), and the resulting force will again be in a direction to the right.

When the hydraulic piston **1078** engages with and/or is disposed within the housing **1084** (as shown in FIG. **54**B), the number of possible gears will increase because the number of different fluid chambers increases. The piston **1078** separates chamber C**1** into two chambers—C**3** and C**4**. This allows 8 pressurization states (three chambers, each pressurized or not pressurized), so the number of possible gears will be equal to seven (each chamber individually, each combination of two of the chambers, and all the chambers). In one example gear, fluid chamber C**3** can be selectively fluidically coupled to a source of hydraulic fluid at a working hydraulic pressure, and the net operating surface area A_{net} will be equal to A**1**, and the resulting force will be in a direction to the right. In another example, the fluid chamber C**3** and the fluid chamber C**2** can both be selectively fluidically coupled to a source of hydraulic fluid at a working pressure and the net operating surface area A_{net} will be equal to (A**1**+A**3**−A**2**−A**4**), and the resulting force will again be in a direction to the right. Thus, in this example, the net operating surface area A_{net} is the same as when fluid chamber C**1** (in FIG. **54**A) is pressurized with hydraulic fluid as described above.

The number of possible gears can also be increased if a hydraulic cylinder(s) is operatively coupled to the other side of the working piston **1074**. Thus, although not shown in FIGS. **54**A and **54**B, one or more hydraulic cylinders can also be operatively coupled to the working piston **1074**. In such an embodiment, the net operating surface area A_{net} can be determined in the same manner as described for previous embodiments.

FIG. **55** illustrates an embodiment of an actuator in which the hydraulic cylinders are disposed within the reservoir or housing in which the working piston is disposed. Such an embodiment may be desirable, for example, to reduce the space required for the particular device to be actuated. An actuator **1112** includes a hydraulic cylinder **1148** and a hydraulic cylinder **1150** each coupled to a housing **1182** and disposed within an interior region defined by the housing **1182**, in which a gas can be compressed and/or from which a fluid can be discharged and/or a into which a liquid can be received. The housing **1182** is configured to contain a volume of fluid within its interior region. The hydraulic cylinder **1148** includes a housing **1184** and a hydraulic piston **1078** movably disposed within an interior region defined by the housing **1184**. The hydraulic cylinder **1150** includes a housing **1185** and a hydraulic piston **1080** movably disposed within an interior region of the housing **1185**. A working piston **1174** is movably disposed within an interior region of the housing **1182** and is coupled to the hydraulic piston **1178** and the hydraulic piston **1180** via a single drive rod R**1**, such that the working piston **1174** can move with movement of the hydraulic piston **1178** and the hydraulic piston **1180**.

The housing **1084** defines within its interior region a hydraulic fluid chamber C**1** and a hydraulic fluid chamber C**2**, and the housing **1085** defines within its interior region a hydraulic fluid chamber C**3** and a hydraulic fluid chamber C**4**. The determination of gears and net operating surface areas associated with a particular gear can be determined in the same or similar manner as described above for previous embodiments, and is, therefore, not described in detail with reference to this embodiment. The hydraulic pistons **1178** and **1180** can be actuated to move within their respective housings

1184 and 1185 and move the working piston 1174 up and down within the housing 1182.

FIG. 56 illustrates an embodiment of an actuator in which the housings of the hydraulic cylinders are fixedly coupled to the working piston within the reservoir or housing in which the working piston is disposed, such that the hydraulic pistons remain stationary and the housings and the working piston move relative to the hydraulic pistons. An actuator 1212 includes a hydraulic cylinder 1248 and a hydraulic cylinder 1280 each disposed within an interior region of a housing 1282 configured to contain a volume of fluid therein. The hydraulic cylinder 1248 includes a housing 1284 and a hydraulic piston 1278 movably disposed within an interior region of the housing 1284, and the hydraulic cylinder 1250 includes a housing 1285 and a hydraulic piston 1280 movably disposed within an interior region of the housing 1285. A drive rod R1 is coupled to the hydraulic piston 1278 and to the housing 1282, and a drive rod R2 is coupled to the hydraulic piston 1280 and to the housing 1282. A working piston 1274 is movably disposed within the interior region of the housing 1282. The working piston is coupled to the housing 1284 and the housing 1285 such that the working piston 1274, the housing 1284, and the housing 1285 can move together relative to the hydraulic piston 1278 and the hydraulic piston 1280 when the actuator 1212 is actuated. Thus, rather than the hydraulic pistons 1278 and 1280 moving relative to the housings 1284 and 1285, respectively, when the actuator 1212 is actuated, the housings 1284 and 1285 (along with the working piston) will move relative to their respective pistons 1278 and 1280.

The housing 1284 defines within its interior region a hydraulic fluid chamber C1 and a hydraulic fluid chamber C2, and the housing 1285 defines within its interior region a hydraulic fluid chamber C3 and a hydraulic fluid chamber C4. The gears and net operating surface areas associated with a particular gear can be determined in the same or similar manner as described above for previous embodiments, and is, therefore, not described in detail with reference to this embodiment.

While various embodiments of the invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Where methods and steps described above indicate certain events occurring in certain order, those of ordinary skill in the art having the benefit of this disclosure would recognize that the ordering of certain steps may be modified and that such modifications are in accordance with the variations of the invention. Additionally, certain of the steps may be performed concurrently in a parallel process when possible, as well as performed sequentially as described above. The embodiments have been particularly shown and described, but it will be understood that various changes in form and details may be made.

For example, the sizes (e.g., diameters, lengths, etc.) of the various components can be varied to provide a desired output of the system. Although FIGS. 7-22 illustrate the various water pumps being different sizes, each of the water pumps can be configured to be the same size and provide the same function and output for a given stage of the system.

Although the liquid in the compressor/expander devices was described above as including water, other liquids can be used, additionally or alternatively. As is to be appreciated, water may naturally condense out of air that is being compressed by the system, and in this respect, may combine with the liquid without adverse impact. Additionally, when used in embodiments of the expander/compressor devices, water may evaporate into air during expansion without having an adverse impact. Other types of liquids, however, may be used in addition to or in place of water. Some examples of such liquids may include additives or entire liquids formulated to prevent freezing, such as glycol, liquids that prevent evaporation, such as glycerin, and/or liquids to prevent foaming. Similarly, although the gas in the compressor/expander device was described above as being air (which is a convenient choice, so that ambient air can be used), other gases can be used, additionally or alternatively.

In addition, although the system 400 was described as having two stages each with two water pumps, and the water pumps are each actuated by two hydraulic cylinders (an upper and a lower hydraulic cylinder), in alternative embodiments, more hydraulic cylinders can be coupled to the top and bottom of a water pump, which can provide additional possible gear modes. In addition, in other embodiments, a system can be configured with a different number of water pumps and/or a different number of stages, which can provide additional possible gear modes. In addition, the systems and methods described herein can be controlled using known computer systems and control system used for such purposes.

Although in the embodiments described above, the driven member that is driven by (or that drives) the hydraulic actuator(s) is a piston that directly or indirectly applies pressure to (or receives pressure from) a gas to be compressed (or expanded), in alternative embodiments the driven member can be any member desired to be driven to supply mechanical power, or to receive mechanical power and be driven. Examples of other applications for the disclosed systems and methods include hydro-mechanical actuators such as those used on commercial aircraft, applications that have a widely varying force profile such as a hydraulic or pneumatic log splitter, lock gates and ocean weirs, and shock absorbers as used on cars and trucks.

The system controller (e.g., 414, 814) can include, for example, a processor-readable medium storing code representing instructions to cause a processor to perform a process. The processor can be, for example, a commercially available personal computer, or other computing or processing device that is dedicated to performing one or more specific tasks. For example, the processor can be a terminal dedicated to providing an interactive graphical user interface (GUI). The processor, according to one or more embodiments, can be a commercially available microprocessor. Alternatively, the processor can be an application-specific integrated circuit (ASIC) or a combination of ASICs, which are designed to achieve one or more specific functions, or enable one or more specific devices or applications. In yet another embodiment, the processor can be an analog or digital circuit, or a combination of multiple circuits.

The processor can include a memory component. The memory component can include one or more types of memory. For example, the memory component can include a read only memory (ROM) component and a random access memory (RAM) component. The memory component can also include other types of memory that are suitable for storing data in a form retrievable by the processor. For example, electronically programmable read only memory (EPROM), erasable electronically programmable read only memory (EEPROM), flash memory, magnetic disk memory, as well as other suitable forms of memory can be included within the memory component. It is recognized than any and all of these memory components can be accessed by means of any form of communication network. The processor can also include a variety of other components, such as for example, co-processors, graphic processors, etc., depending upon the desired functionality of the code.

The processor can be in communication with the memory component, and can store data in the memory component or retrieve data previously stored in the memory component. The components of the processor can be configured to communicate with devices external to the processor by way of an input/output (I/O) component. According to one or more embodiments, the I/O component can include a variety of suitable communication interfaces. For example, the I/O component can include, for example, wired connections, such as standard serial ports, parallel ports, universal serial bus (USB) ports, S-video ports, local area network (LAN) ports, small computer system interface (SCCI) ports, analog to digital interface input devices, digital to analog interface output devices, and so forth. Additionally, the I/O component can include, for example, wireless connections, such as infrared ports, optical ports, Bluetooth® wireless ports, wireless LAN ports, or the like. The processor can also be connected to a network, which may be any form of interconnecting network including an intranet, such as a local or wide area network, or an extranet, such as the World Wide Web or the Internet. The network can be physically implemented on a wireless or wired network, on leased or dedicated lines, including a virtual private network (VPN).

What is claimed is:

1. An apparatus suitable for use in a compressed gas-based energy storage and recovery system, the apparatus comprising:

a pneumatic cylinder having a working piston disposed therein for reciprocating movement in the pneumatic cylinder, the working piston dividing the pneumatic cylinder into, and defining therewith, a first pneumatic chamber and a second pneumatic chamber;

a first hydraulic actuator coupled to the working piston to drive, or be driven by, the working piston, the first hydraulic actuator including a first hydraulic cylinder and a first hydraulic piston disposed for reciprocating movement in the first hydraulic cylinder, the first hydraulic piston dividing the first hydraulic cylinder into, and defining therewith, a first hydraulic chamber and a second hydraulic chamber;

a second hydraulic actuator coupled to the working piston to drive, or be driven by, the working piston, the second hydraulic actuator including a second hydraulic cylinder and a second hydraulic piston disposed for reciprocating movement in the second hydraulic cylinder, the second hydraulic piston dividing the second hydraulic cylinder into, and defining therewith, a third hydraulic chamber and a fourth hydraulic chamber; and

a hydraulic controller fluidically coupleable to the first hydraulic actuator and the second hydraulic actuator, the hydraulic controller operable to cause the first hydraulic actuator to displace the working piston in a first direction to compress gas contained in the first pneumatic chamber and in a second direction to compress gas contained in the second pneumatic chamber, the hydraulic controller operable to selectively provide or not provide pressurized hydraulic fluid to one or more of the first, second, third, and fourth hydraulic chambers in at least four combinations, each combination producing a different net actuator force on the working piston acting in the first direction, each combination having a different net hydraulic piston area,

wherein, in a first one of the combinations, pressurized hydraulic fluid is provided to the first hydraulic chamber and not provided to the second hydraulic chamber and, wherein, in a second one of the combinations, pressurized hydraulic fluid is provided to the second hydraulic chamber and not provided to the first hydraulic chamber.

2. The apparatus of claim **1**, wherein the hydraulic controller is further operable to allow the working piston to be moved in the first direction by compressed gas entering the second pneumatic chamber to cause the first hydraulic actuator to displace a first volume of hydraulic fluid.

3. The apparatus of claim **2**, wherein the hydraulic controller is further operable to allow the working piston to be moved in the second direction by compressed gas entering the first pneumatic chamber to cause the second hydraulic actuator to displace a second volume of hydraulic fluid.

4. The apparatus of claim **1**, further comprising a connecting rod coupling the first hydraulic actuator and the second hydraulic actuator.

5. The apparatus of claim **1**, wherein the working piston is disposed between the first hydraulic actuator and the second hydraulic actuator.

6. The apparatus of claim **1**, wherein the first hydraulic actuator is coupled to the working piston by a first piston rod coupled to the working piston and to the first hydraulic piston.

7. The apparatus of claim **6**, wherein the second hydraulic actuator is coupled to the working piston by a second piston rod coupled to the working piston and to the second hydraulic piston.

8. An apparatus suitable for use in a compressed gas-based energy storage and recovery system, the apparatus comprising:

a pneumatic cylinder having a working piston disposed therein for reciprocating movement in the pneumatic cylinder, the working piston dividing the pneumatic cylinder into, and defining therewith, a first pneumatic chamber and a second pneumatic chamber;

a first hydraulic actuator coupled to the working piston and having a first hydraulic piston, the first hydraulic piston dividing the first hydraulic cylinder into, and defining therewith, a first hydraulic chamber and a second hydraulic chamber;

a second hydraulic actuator coupled to the working piston and having a second hydraulic piston, the second hydraulic piston dividing the second hydraulic cylinder into, and defining therewith, a third hydraulic chamber and a fourth hydraulic chamber; and

a hydraulic controller fluidically coupleable to the first hydraulic actuator and the second hydraulic actuator, the hydraulic controller operable with a pressurized hydraulic fluid to cause at least the first hydraulic actuator to produce a selected hydraulic actuator force to displace the working piston in a first direction such that gas contained in the first pneumatic chamber is compressed from a first pressure to a second pressure,

the hydraulic controller further operable with the pressurized hydraulic fluid to cause at least the second hydraulic actuator to produce a selected hydraulic actuator force to displace the working piston in a second direction such that gas contained in the second pneumatic chamber is compressed from a third pressure to a fourth pressure,

the hydraulic controller operable to selectively provide or not provide pressurized hydraulic fluid to one or more of the first, second, third, and fourth hydraulic chambers in at least four combinations, each combination producing a different net actuator force on the working piston acting in the first direction, each combination having a different net hydraulic piston area,

wherein, in a first one of the combinations, pressurized hydraulic fluid is provided to the first hydraulic cham-

ber and not provided to the second hydraulic chamber and, wherein, in a second one of the combinations, pressurized hydraulic fluid is provided to the second hydraulic chamber and not provided to the first hydraulic chamber.

9. The apparatus of claim **8**, further comprising a connecting rod disposed between, and coupled to, the first hydraulic actuator and the second hydraulic actuator.

10. The apparatus of claim **8**, wherein the working piston is disposed between the first hydraulic actuator and the second hydraulic actuator.

11. The apparatus of claim **8**, wherein the first hydraulic actuator is disposed between the second hydraulic actuator and the working piston.

12. The apparatus of claim **8**, wherein the first hydraulic actuator is coupled to the working piston by a first piston rod and the second hydraulic actuator is coupled to the first hydraulic actuator by a second piston rod.

13. The apparatus of claim **8**, wherein the pressurized hydraulic fluid is in fluidic communication with the high pressure side of a hydraulic pump.

14. An apparatus suitable for use in a compressed gas-based energy storage and recovery system, the apparatus comprising:

a pneumatic cylinder having a working piston disposed therein for reciprocating movement in the pneumatic cylinder, the working piston dividing the pneumatic cylinder into, and defining therewith, a first pneumatic chamber and a second pneumatic chamber;

a first hydraulic actuator coupled to the working piston to drive, or be driven by, the working piston, the first hydraulic actuator including a first hydraulic cylinder and a first hydraulic piston disposed for reciprocating movement in the first hydraulic cylinder, the first hydraulic piston having a first diameter and dividing the first hydraulic cylinder into, and defining therewith, a first hydraulic chamber and a second hydraulic chamber; and

a second hydraulic actuator coupled to the working piston to drive, or be driven by, the working piston, the second hydraulic actuator including a second hydraulic cylinder and a second hydraulic piston disposed for reciprocating movement in the second hydraulic cylinder, the second hydraulic piston having a second diameter, different than the first diameter, the second hydraulic piston dividing the second hydraulic cylinder into, and defining therewith, a third hydraulic chamber and a fourth hydraulic chamber; and

a hydraulic controller fluidically coupleable to the first hydraulic actuator and the second hydraulic actuator, the hydraulic controller operable to cause the first hydraulic actuator to displace the working piston in a first direction to compress gas contained in the first pneumatic chamber and in a second direction to compress gas contained in the second pneumatic chamber, the hydraulic controller operable to selectively provide or not provide pressurized hydraulic fluid to one or more of the first, second, third, and fourth hydraulic chambers in at least four combinations, each combination producing a different net actuator force on the working piston acting in the first direction, each combination having a different net hydraulic piston area,

wherein, in a first one of the combinations, pressurized hydraulic fluid is provided to the first hydraulic chamber and not provided to the second hydraulic chamber and, wherein, in a second one of the combinations, pressurized hydraulic fluid is provided to the second hydraulic chamber and not provided to the first hydraulic chamber.

15. The apparatus of claim **14**, wherein the first hydraulic chamber includes a first hydraulic fluid port and the second hydraulic chamber includes a second hydraulic fluid port, the first hydraulic chamber having a first effective hydraulic piston surface area upon which application of a pressurized hydraulic fluid communicated to the first hydraulic chamber via the first hydraulic port produces a first hydraulic actuator force on the working piston acting in the first direction, the second hydraulic chamber having a second effective hydraulic piston surface area, different than the first effective hydraulic piston surface area upon which application of a pressurized hydraulic fluid communicated to the second hydraulic chamber via the second hydraulic port produces a second hydraulic actuator force, different than the first hydraulic actuator force, on the working piston acting in the second direction.

16. The apparatus of claim **14**, wherein the third hydraulic chamber includes a third hydraulic fluid port and the fourth hydraulic chamber includes a fourth hydraulic fluid port, the third hydraulic chamber having a third effective hydraulic piston surface area, upon which application of a pressurized hydraulic fluid communicated to the third hydraulic chamber via the third hydraulic port produces a third hydraulic actuator force on the working piston acting in the first direction the fourth hydraulic chamber having a fourth effective hydraulic piston surface area, different than the third effective hydraulic piston surface area, upon which application of a pressurized hydraulic fluid communicated to the fourth hydraulic chamber via the fourth hydraulic port produces a fourth hydraulic actuator force, different than the third hydraulic actuator force, on the working piston acting in the second direction.

17. The apparatus of claim **14**, wherein the working piston is disposed between the first hydraulic actuator and the second hydraulic actuator.

18. The apparatus of claim **14**, wherein the first hydraulic actuator is coupled to the working piston by a first piston rod coupled to the working piston and to the first hydraulic piston, and the second hydraulic actuator is coupled to the working piston by a second piston rod coupled to the working piston and to the second hydraulic piston.

* * * * *